AN ANALYSIS OF SHORELINE CHANGE AT LITTLE LAGOON, ALABAMA

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THESIS

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ABSTRACT

In Alabama, the term "coastal shoreline" applies to the gulf shoreline and the shorelines of estuaries, bays, and sounds connected to the Gulf of Mexico and subject to its tides. However, Alabama shoreline studies have yet to include Little Lagoon, which has been connected to the Gulf of Mexico for most of the last 200 years, according to historical charts. This study used historical nautical charts, aerial photographs, and LIDAR derived shorelines from 1917 to 2004 to analyze shoreline change on Little Lagoon and its adjacent gulf shoreline. The high water line was used as the common reference feature, and all shorelines were georeferenced, projected, and digitized in a Geographic Information System.

Between 1917 and 2001, the gulf shoreline eroded an average of 40m over 12.7km, with some transects eroding almost 120m while others accreted almost 60m. The greatest changes to the gulf shoreline were found near natural inlets, downdrift of jetties, and coincident with nourishment projects. Between 1955 and 1997, Little Lagoon shrank 0.5%, or 51.4km^2, from 10,285.9km^2 to 10,234.5km^2. The greatest changes to Little Lagoon were found on its southern shoreline and near inlets, human development, and hurricane overwash fans. A correlation analysis conducted on the gulf shoreline and Little Lagoon's southern shoreline showed that although weak overall correlation values exist when the entire 12.7km study area is compared, strong correlation values are obtained in some areas when compared over one kilometer sections. The strongest correlations were found in the same locations as the greatest changes.

INTRODUCTION

The effects of coastal engineering on beach dynamics have long been recognized, but scientists have yet to develop a mathematical model that can adequately predict such effects. Some coastal researchers now believe that a focus on qualitative, rather than quantitative, approaches will improve understanding of coastal processes (Cooper and Pilkey, 2004a). An understanding of beach behavior in response to future engineering can be gained by observing coastal morphology of the proposed engineering site or on a shoreline under similar conditions. Unfortunately, many miles of coastline have not been scientifically observed until recently, or in some cases not at all. However, aerial photography from as far back as the 1940's are available. Such photos often contain valuable information about coastal morphology, particularly for engineered tidal inlets (Fitzgerald *et al*., 2003). Historic maps and nautical charts dating back to the 1800's are also available. This research used free or relatively low-cost, easily obtained aerial photography from 1940 to 2005, digitized nautical charts from 1917 to 1981, and historical maps from 1804 to 1950 to study shoreline change near Gulf Shores, Alabama.

In Alabama, the term "coastal shoreline" applies to the Gulf of Mexico shoreline and estuaries, bays, and sounds connected to the Gulf of Mexico and subject to its tides (Smith, 1986). Throughout most of the last 200 years, Little Lagoon has been connected to the Gulf of Mexico through natural tidal inlets. Since 1981, an engineered tidal inlet known as Little Lagoon Pass has connected the two. However, previous studies of Alabama shoreline change (Hardin *et al*., 1976; Smith, 1991; Douglas *et al*., 1998) have yet to include Little Lagoon. When measuring shoreline change, studies need to consider a wider range of beach types, like embayed beaches, including lagoons (Stephenson and Brander, 2003). The National Assessment of

Shoreline Change (Morton, 2004) states that bay and lagoon shorelines show the longest stretches of erosion. This study will analyze changes to Little Lagoon's 30.5km shoreline and the adjacent 12.7km of gulf shoreline, and examine their relationship.

Study Area

Alabama's only mainland shore is a sandy stretch of beach in Baldwin County (Figure 1).

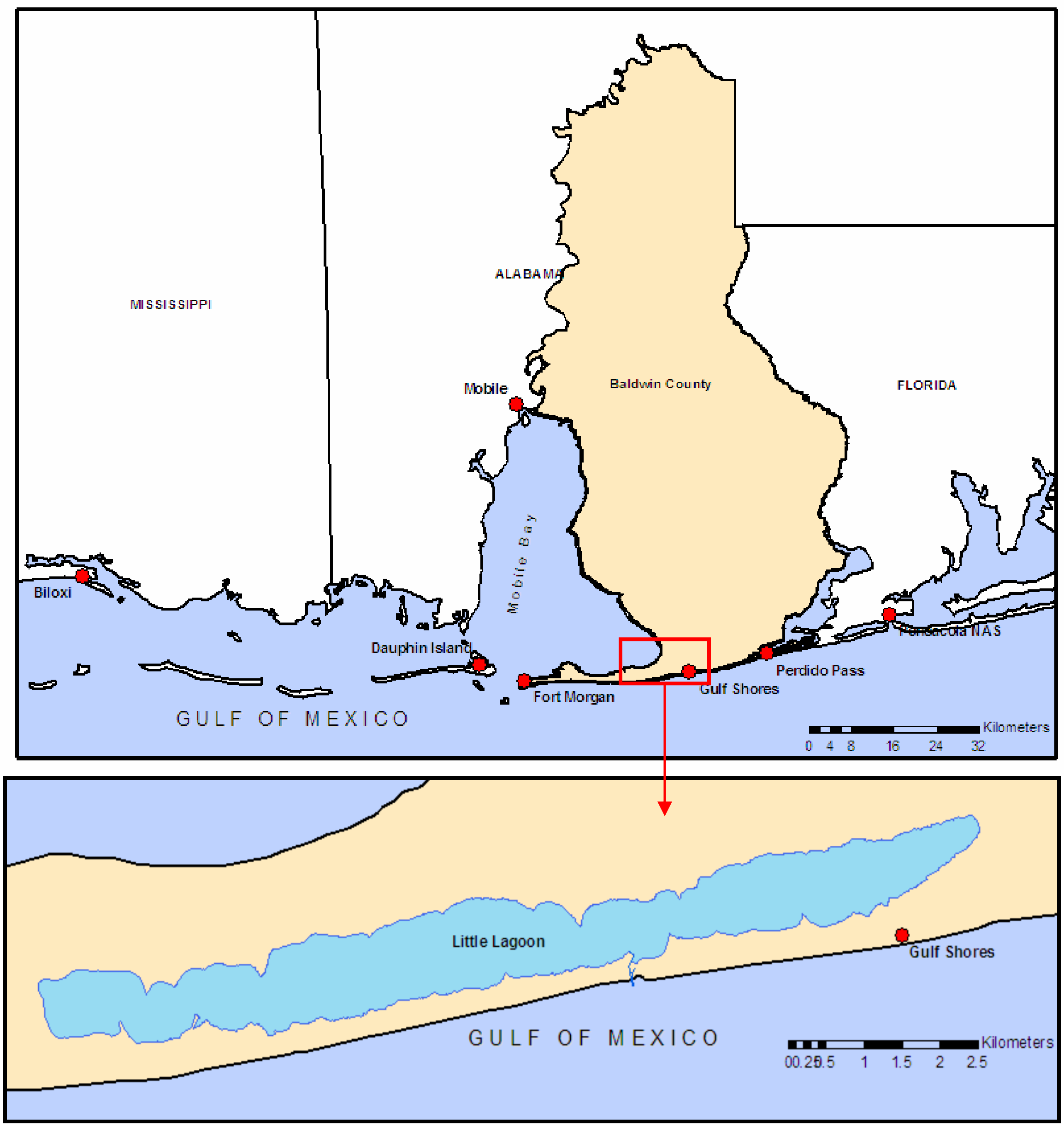

Figure 1 (Study Area)

Approximately 50km in length, it spans from Mobile Point in the west to just east of Perdido Pass in the east. Little Lagoon is just west of the city of Gulf Shores. Little Lagoon is approximately 12.6km in length and over 1km wide at its widest point. The narrow strip of land between the gulf shoreline and the lagoon's southern shoreline is less than 180m at its narrowest point. The study area is 12.7km in length on the Gulf of Mexico shoreline and includes all of Little Lagoon's shoreline.

Little Lagoon is located at approximately North 30°15' latitude, West 087°45' longitude. Official precipitation totals at Pensacola Naval Air Station, 40km to the east, averaged 63.11" annually between 1971 and 2000 (Table 1). There is no classified wet or dry season, but July

Dauphin Island – Average Temperatures 1971-2000

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Max	58.1	60.8	67.1	73.5	80.8	86.5	88.8	88.7	85.3	77.2	68.6	61.0	74.7
Mean	51.3	54.0	60.9	67.6	75.3	80.8	82.9	83.0	79.8	71.0	62.1	54.3	68.6
Min	44.5	47.1	54.6	61.7	69.7	75.0	76.9	77.2	74.2	64.7	55.5	47.6	62.4

Dauphin Island – Average Precipitation 1971-2000

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Prec	6.12	5.11	6.23	4.46	5.25	5.02	7.27	6.97	4.99	3.61	4.58	4.64	64.25

Pensacola NAS – Average Temperatures 1971-2000

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Max	61.2	64.2	69.6	75.4	82.6	88.1	90.2	89.9	86.7	79.3	70.7	63.9	76.8
Mean	51.9	54.8	60.6	66.3	73.9	79.9	82.3	82.0	78.5	69.2	60.8	54.5	67.9
Min	42.6	45.3	51.6	57.1	65.1	71.6	74.3	74.0	70.2	59.1	50.9	45.0	58.9

Pensacola NAS – Average Precipitation 1971-2000

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Prec	5.72	4.86	6.32	3.97	4.41	5.17	7.09	6.11	6.75	4.26	4.43	4.02	63.11

Pensacola NAS – Average Winds 1930-1996

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Dir	N	N	N	N	N	N	ESE	ESE	ESE	SE	SE	SE	N
Spd	10	11	11	12	10	10	8	7	9	9	9	10	10

Mobile – Average Winds 1930-1996

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Dir	N	N	N	N	SE	SE	SE	SE	S	S	S	S	S
Spd	10	11	11	10	9	6	7	7	8	8	9	10	9

Biloxi – Average Winds 1930-1996

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Dir	N	N	SSE	SSE	SSE	SSW	SSW	N	NNE	NNE	N	N	N
Spd	7	7	7	7	6	6	5	5	5	5	6	7	6

Table 1 (Modified from National Climate Data Center reports)

through September are among the rainiest months while October through December are among the driest. The warmest month is July with an average high of 90.2° F, and the coldest month is January with an average low of 42.6° F. Based on official wind data for Pensacola NAS from 1930 to 1996, winds are predominantly from the north at 10kts per hour, but vary seasonally. During the winter and spring the majority of winds are from the north at 10 to 12kts, during the summer winds are from the east-southeast at 7 to 9kts, and during the fall winds are from the southeast at 9 to 10kts.

According to Davies's (1980) distribution of tidal ranges, the study area is micro-tidal, with tides ranging less than 2m. The mean wave height is 0.9m and the average wave period is 5 seconds (http://chl.erdc.usace.army.mil). Beach face angles for Baldwin County average 6.9° (Smith and Parker 1990). Nearshore sediment is transported from east to west at about 45,000m^3 per year (Stone and Stapor 1996). The mean sea-level trend is between +2.14mm per year at Pensacola and +2.43mm per year at Dauphin Island (http://www.co-ops.nos.noaa.gov).

Inlets and Hurricanes

Little Lagoon has been connected to the Gulf of Mexico through natural and human-made tidal inlets for most of the last 200 years. Over the years, the inlets have opened, relocated, or even closed, but even then Gulf waters probably interacted during the highest high tides (Hardin, *et al*, 1976). New inlets may compete with existing inlets, promoting their closure (Kraus and Wamsley, 2003). As documented on the historic maps (listed in Appendix A), nautical charts' digitized shorelines, and aerial photography used in this research, the study area has hosted tidal inlets at three main areas between 1804 and 2005 (Figure 2).

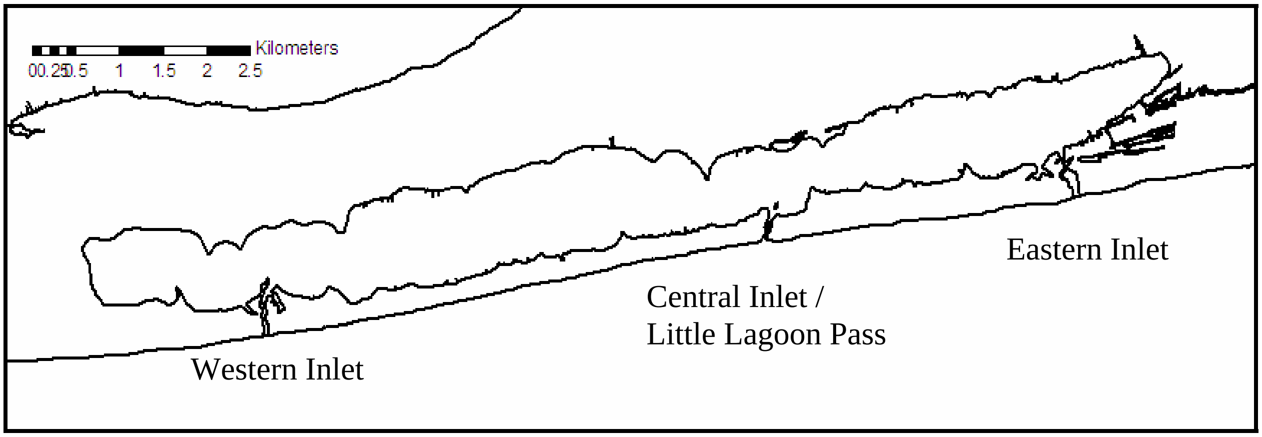

Figure 2 (Locations of natural inlets during last 200 years)

Between 1804 and 1846 only one inlet was depicted, and it was 2km from the west end of the lagoon. On 1853 and 1856 maps two inlets existed, the same one in the west and another about 1.3km from the eastern end of the lagoon. In 1860 the only inlet shown was the one in the west, but by 1864 both inlets were open again. In 1866 only the eastern inlet was depicted, but in 1872 the western inlet was the only one open. Both the eastern and western inlets were shown on a 1879 map. In 1882 only the western inlet was open, and there it remained until 1909 when the only inlet depicted was in the east. Both inlets were open on a 1911 map. No inlets appeared in 1915, but a 1917 nautical chart depicted the eastern inlet open. No inlets appeared to be open on a 1928 map, but in 1930 the eastern inlet was again open. A 1934 nautical chart showed that eastern inlet was closed, but it only covered the eastern half of the lagoon so it is impossible to tell if the western inlet was open at that time. No inlets were distinguishable in 1940 and 1949 county aerial photomosaics, or shown on a 1950 map. Aerial photographs for 1955, 1960, and 1970 showed that the western inlet was open, but in 1974 photos there was no clear-cut inlet. Topographic charts for 1976 depicted an inlet near the center of the lagoon, 4.5km from the eastern end. In 1981 jetties were constructed to stabilize that natural inlet. In 2004 and 2005, Hurricanes Ivan and Katrina, respectively, opened a natural inlet in the west (Figure 3).

Figure 3 (Post-Hurricane Ivan - Sept 16, 2004, Courtesy of NOAA)

Since 1959, 24 hurricanes and tropical storms have affected the study area with associated storm tides or storm surges (Table 2). All of these storms made landfall on the gulf coast between June and October, but almost half (11) occurred during September. By applying the same distances of landfall from Little Lagoon as the 24 storms mentioned above, it may be reasoned that 87 storms impacted the study area between 1851 and 2005 (Tables 2 & 3 combined). Again, all of these storms made landfall between June and October, with 4 occurring in June, 9 in July, 17 in August, 41 in September, and 16 in October.

Though there is no definitive evidence that hurricanes were responsible for the opening or relocating of tidal inlets over the last 200 years, it is interesting that a few of the years in which inlets moved corresponded with storm years. For example, between 1846 and 1853 an additional inlet was opened, and in 1852 a Category 3 hurricane made landfall less than 100km west of Little Lagoon. Also, in 1904 the western inlet was open, but in 1909 it was in the east. Coincidently, in 1906 a Category 2 hurricane made landfall approximately 100km to the west. In 1979, Hurricane Frederic made landfall just west of the study area, and aerial photos taken over a month later still show the evidence of inlets that were opened by the storm. As mentioned before, Hurricanes Ivan and Katrina opened additional inlets in 2004 and 2005 respectively.

Possibly there are other instances, but without knowing exactly when the historical maps were penned it is impossible to draw any further conclusions.

Tropical Storms and Hurricanes from 1959 to 2005

Date	Name	Cat	City nearest landfall	Coordinates	St Surge*	St Tide*
1959/10/08	Irene	TS	Orange Beach, AL	(30.3,87.6)		1-2'
1960/09/15	Ethel	1	Biloxi, MS	(30.4,89.0)		2-5'
1964/10/03	Hilda	3	Franklin, LA	(29.6,91.6)		2-6'
1965/09/09	Betsy	4	Grand Isle, LA	(29.1,90.1)		12'
1969/08/17	Camille	5	Bay St. Louis, MS	(30.2,89.4)		5-15'
1975/09/23	Eloise	3	Destin, FL	(30.3,86.3)		1-2'
1979/07/11	Bob	1	Houma, LA	(29.1,90.6)		1-3'
1979/09/13	Frederic	3	Dauphin Island, AL	(30.3,88.2)		11-12'
1985/09/02	Elena	3	Biloxi, MS	(30.4,89.2)	5-8'	3-5'
1985/10/31	Juan	TS	Gulf Shores, AL	(30.2,87.8)		3-6'
1988/09/10	Florence	1	Buras, LA	(29.1,89.3)	1-2'	
1992/08/26	Andrew	3	Franklin, LA	(29.6,91.5)		3-6'
1995/08/03	Erin	1	Pensacola Beach, FL	(30.3,87.2)		3-4'
1995/10/04	Opal	3	Pensacola Beach, FL	(30.3,87.1)		5-14'
1997/07/19	Danny	1	Fort Morgan, AL	(30.2,88.1)	6'	2-5'
1998/09/03	Earl	1	Panama City, FL	(30.1,85.7)		2-3'
1998/09/28	Georges	2	Biloxi, MS	(30.4,88.9)	8-9'	7-12'
2002/09/14	Hanna	TS	Buras, LA	(29.1,89.1)		3-4'
2002/09/26	Isidore	TS	Grand Isle, LA	(29.1,90.3)		5-6'
2004/09/16	Ivan	3	Gulf Shores, AL	(30.2,87.9)	10-15'	
2005/06/11	Arlene	TS	Orange Beach, AL	(30.3,87.5)		2-4'
2005/07/06	Cindy	1	Grand Isle, LA	(29.2,90.1)	3-4'	3-7'
2005/07/10	Dennis	3	Santa Rosa Island, FL	(30.4,87.1)	3-5'	3-6'
2005/08/29	Katrina	3	Buras, LA	(29.3,89.6)	5-10'	6-11'

*Storm Surge and Storm Tide data are for the study area and based on measurements available from the National Hurricane Center reports. Storm Surge and Storm Tide were estimated from nearby measurements since no recording devices are established in the study area.

Table 2 (Storm data from 1959 to 2005)

Tropical Storms and Hurricanes from 1851 to 1958*

Date	Name	Cat	City nearest landfall	Coordinates
1851/08/23	Not Named	3	Panama City, FL	(30.1,85.7)
1852/08/26	Not Named	3	Pascagoula, MS	(30.3,88.6)
1855/09/16	Not Named	3	Gulfport, MS	(30.2,89.4)
1856/08/10	Not Named	4	Morgan City, LA	(29.2,91.1)
1856/08/31	Not Named	2	Panama City, FL	(30.2,85.9)
1859/09/15	Not Named	1	Dauphin Island, AL	(30.2,88.1)
1860/08/12	Not Named	3	Biloxi, MS	(30.4,89.0)
1860/09/15	Not Named	2	Gulfport, MS	(30.3,89.3)
1860/10/02	Not Named	2	Morgan City, LA	(29.5,91.4)
1867/10/05	Not Named	2	Buras, LA	(29.2,89.4)
1869/09/05	Not Named	1	Grand Isle, LA	(29.2,90.0)
1872/07/11	Not Named	TS	Biloxi, MS	(30.4,89.0)
1877/09/19	Not Named	1	Destin, FL	(30.4,86.6)
1877/10/03	Not Named	3	Mexico Beach, FL	(29.9,85.5)
1879/09/01	Not Named	3	Morgan City, LA	(29.3,91.3)
1881/08/03	Not Named	TS	Pascagoula, MS	(30.4,88.3)
1882/09/10	Not Named	3	Ft Walton Beach, FL	(30.4,86.7)
1885/09/27	Not Named	TS	Biloxi, MS	(30.4,88.8)
1887/06/14	Not Named	TS	Biloxi, MS	(30.4,88.7)
1887/07/27	Not Named	1	Destin, FL	(30.4,86.6)
1887/10/19	Not Named	TS	Biloxi, MS	(30.4,88.8)
1888/08/19	Not Named	2	Houma, LA	(29.1,90.7)
1889/09/23	Not Named	TS	Gulf Shores, AL	(30.2,87.8)
1893/09/07	Not Named	2	Morgan City, LA	(29.2,91.1)
1893/10/02	Not Named	4	Grand Isle, LA	(29.3,89.8)
1894/08/07	Not Named	TS	Gulf Shores, AL	(30.3,87.6)
1894/10/09	Not Named	3	Panama City, FL	(30.1,85.7)
1895/08/16	Not Named	TS	Biloxi, MS	(30.4,88.7)
1896/07/07	Not Named	2	Destin, FL	(30.4,86.5)
1900/09/13	Not Named	TS	Pascagoula, MS	(30.3,88.7)
1901/08/15	Not Named	1	Biloxi, MS	(30.4,88.8)
1902/10/10	Not Named	TS	Pensacola, FL	(30.3,87.3)

Date	Name	Cat	City nearest landfall	Coordinates
1903/09/13	Not Named	1	Panama City, FL	(30.0,85.6)
1906/09/27	Not Named	2	Biloxi, MS	(30.3,88.7)
1907/09/21	Not Named	TS	Gulfport, MS	(30.4,88.9)
1909/09/20	Not Named	3	Morgan City, LA	(29.2,91.2)
1911/08/11	Not Named	1	Orange Beach, AL	(30.3,87.4)
1912/09/14	Not Named	1	Pascagoula, MS	(30.4,88.4)
1914/09/18	Not Named	TS	Bon Secour, AL	(30.4,87.9)
1915/09/04	Not Named	1	Mexico Beach, FL	(29.9,85.4)
1915/09/29	Not Named	2	Grand Isle, LA	(29.1,90.1)
1916/07/05	Not Named	3	Gulfport, MS	(30.4,88.9)
1916/10/18	Not Named	3	Pensacola, FL	(30.3,87.4)
1917/09/29	Not Named	2	Destin, FL	(30.4,86.6)
1920/09/21	Not Named	1	Morgan City, LA	(29.1,90.9)
1922/10/17	Not Named	TS	Gulf Shores, AL	(30.3,87.6)
1923/10/16	Not Named	2	Morgan City, LA	(29.2,91.2)
1923/10/17	Not Named	TS	Gulfport, MS	(30.4,89.0)
1924/09/15	Not Named	1	Panama City, FL	(30.1,85.8)
1926/08/26	Not Named	2	Morgan City, LA	(29.2,91.2)
1926/09/21	Not Named	2	Ft Morgan, AL	(30.2,88.0)
1932/09/01	Not Named	1	Ft Morgan, AL	(30.2,88.0)
1934/06/16	Not Named	1	Morgan City, LA	(29.2,91.0)
1934/10/06	Not Named	TS	Dauphin Island, AL	(30.2,88.2)
1936/07/31	Not Named	1	Destin, FL	(30.4,86.6)
1939/06/16	Not Named	TS	Ft Morgan, AL	(30.2,87.9)
1947/09/08	Not Named	TS	Dauphin Island, AL	(30.2,88.3)
1947/09/19	Not Named	1	New Orleans, LA	(29.8,89.3)
1948/09/04	Not Named	1	Grand Isle, LA	(29.1,90.4)
1950/08/31	Baker	1	Ft Morgan, AL	(30.1,87.9)
1953/09/26	Florence	1	Destin, FL	(30.3,86.2)
1956/09/24	Flossy	1	Destin, FL	(30.4,86.4)
1957/09/08	Debbie	TS	Destin, FL	(30.4,86.4)

*There were no storms affecting the study area in 1958.

Table 3 (Storm data from 1851 to 1958)

Spatial and Temporal Scale

The previously mentioned studies of Alabama's shoreline were broader in scope than this research, covering over 800km of total shoreline and about 70km of gulf beachfront, which may explain their lack of great detail for any one particular area. However, when studies conducted by Stone and Stapor (1996) and Cipriani and Stone (2001) are combined, they identify 23 separate sediment transport cells between Apalachicola Bay, Florida, and the Mississippi Barrier Islands, which in itself demands that shorelines be studied on a larger scale, or smaller area. To further illustrate the need for larger scale, an example can be given from this study. As will be discussed later, the average change of the gulf shoreline from 1917 to 2001 is –40m, but even on the relatively short 12.7km strip of beach measurements range from almost –120m to over +60m. It is important to understand why the changes occurred where they did and when they did.

Gibeaut (2000) defined long-term change as occurring over tens to thousands of years, short-term change occurring over several seasons to 10 years, and episodic change occurring in response to a single storm. Cowell and Thom (1994) defined times scales as either 1) *instantaneous* for seconds to days, 2) *event* for days to years, 3) *engineering* for years to centuries, or 4) *geological* spanning decades to millennia. Shoreline studies often focus on long-term change or engineering time scales. However, long time periods can overlook important changes. For example, as mentioned before, this study area's gulf shoreline eroded an average of 40m between 1917 and 2001. Oddly enough, the average change for the same area from 1917 to 1955 is –40m. So does that mean all of the change between 1917 and 2001 actually occurred prior to 1955? In fact, some of the most dramatic changes happened after 1955. For this study, change will be analyzed for periods ranging from 4 to 15 years, with the exception being the 1917 to 1955 time period.

Problem Statement

Because previous studies of Alabama shorelines gave little attention to the influence of tidal inlets, there is no literature describing the changes that did occur on the shoreline south of Little Lagoon. Also, there is no literature describing the location and nature of changes on Little Lagoon itself. As the area continues to develop (Figure 4) coincident with increased storm activity and relative sea level rise, the likelihood of repeated breaching of the narrow barrier between the Gulf of Mexico and Little Lagoon increases. Eventually, an alternative to the existing jettied inlet at Little Lagoon Pass may be sought, and knowledge greater than general coastal processes and mathematical models will be needed. By analyzing shoreline change in larger-scales and shorter-terms, this study will provide not only quantitative measurement but also the qualitative analysis called for by Cooper and Pilkey (2004b).

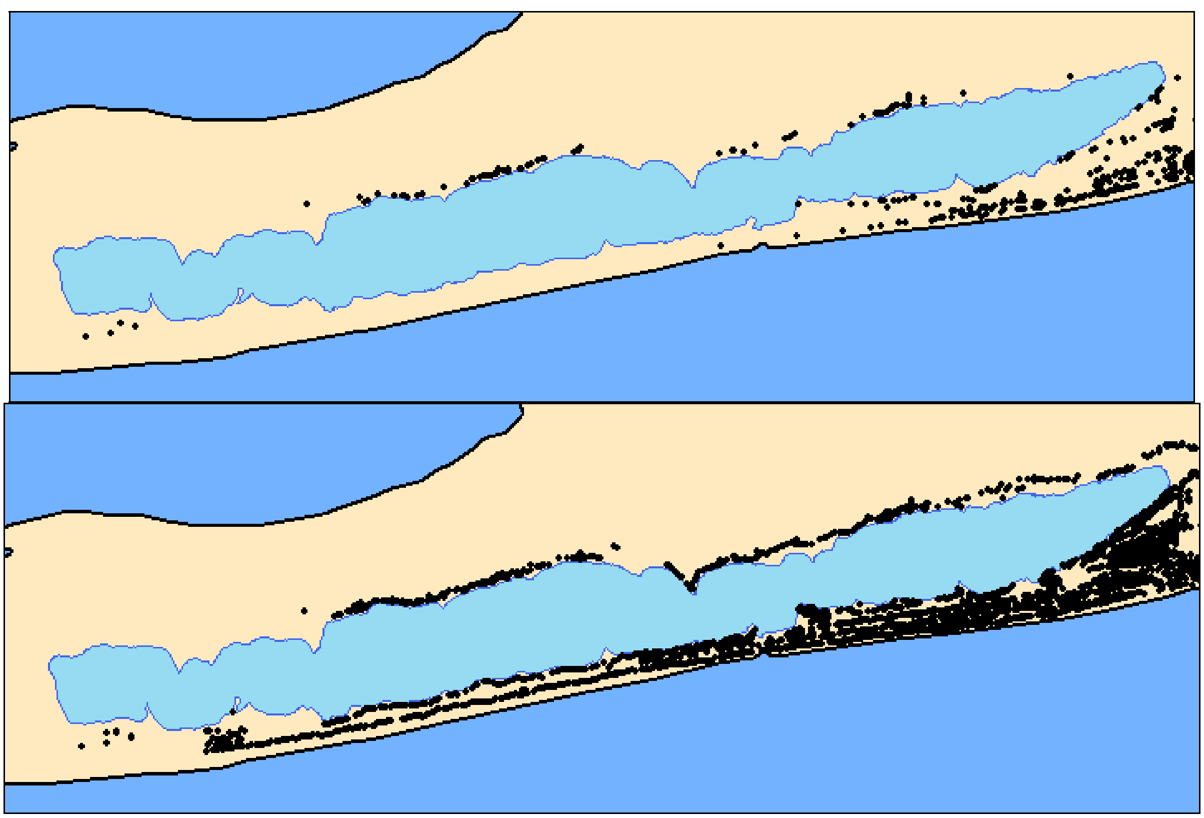

Figure 4 (Upper: development in 1955; Lower: development in 2004)

COASTAL PROCESSES

The beach acts as the seaward protection for the coast. It extends from the low tide line landward to the next geomorphologic feature. As shown in Figure 5, the beach can be further divided into the fore shore and the backshore. The foreshore, or beachface, includes the inter-tidal portion of the beach and extends landward to the berm. It includes the swash zone, where waves uprush and backwash as they meet the shore. The backshore extends from the berm landward to the next feature, which in the case of this study area would be human development. The backshore will not be discussed in this study, except to say that overwash may occur during storms. Because their adjacent waters directly influence coastal landscapes, we will also discuss the nearshore environment. The nearshore includes the shallow marine waters extending from the low tide line seaward to include sand bars.

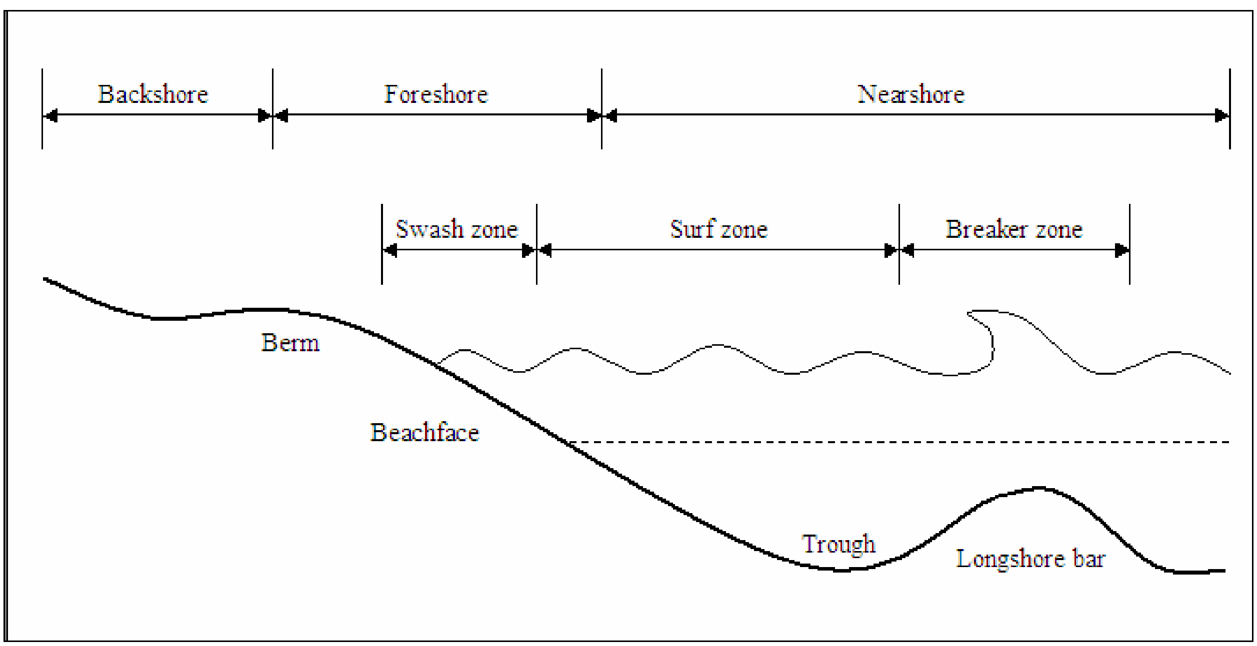

Figure 5 (Beach profile)

The planform shape of a beach is related to the direction of wave approach (Woodroffe, 2003). Breaking waves produce obvious interaction with the beach, placing sediments into temporary suspension. Nearshore currents then move the suspended sediment. If waves approach parallel to the shore they do not move sediment alongshore, and the beach tends to be curved, or swash-aligned (Stapor, 1971; Davies, 1980). However, waves approaching the shore at approximately 30-45° can produce the greatest rates of sediment transport, and the beach tends to be long and straight, or drift-aligned. Rhythmic crescentic features formed by swash action, called beach cusps, can accentuate the overall shape of a beach (Figure 6). They occur in a series with varying distances, like swash cusps spaced 8-25m, storms cusps spaced 70-120m, and giant cusps spaced 700-1500m (Dolan, 1971). Beach cusps may be self-organized features that develop by positive feedback between swash flow and morphology, accentuating random morphological irregularities (Werner and Fink, 1993; Coco et al., 1999). The beach moulds to adjust to changes in wave energy by the movement of sediment (Reeve *et al*., 2001). Process adjustments may be instantaneous, but morphology will lag because of the time required to move sediments. The beach will continue to change in an attempt to reach equilibrium.

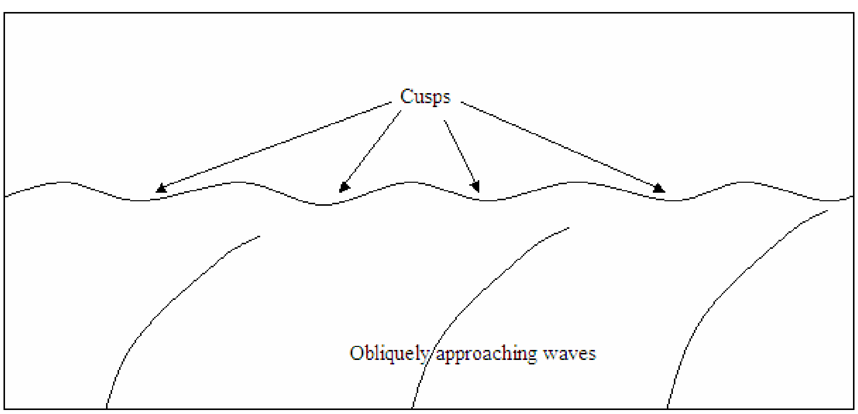

Figure 6 (Beach cusps on a drift-aligned beach)

The relationship between beach profile and wave conditions promotes negative feedback cycles. Under calm conditions, sand is transported onshore resulting in beach accretion. As it builds up, the slope of the beach steepens until it is sufficiently altered to stop onshore transport. During storm conditions, sand is transported offshore resulting in the development of an offshore bar. Wave energy is reduced by waves breaking on the bar before reaching the shore, limiting further erosion.

Currents produced by waves are among the most important processes that generate change in the beach (Davis and Fitzgerald, 2004). They include longshore currents, rip currents, and the onshore-offshore currents, and are responsible or for the transport of sediment (Figure 7).

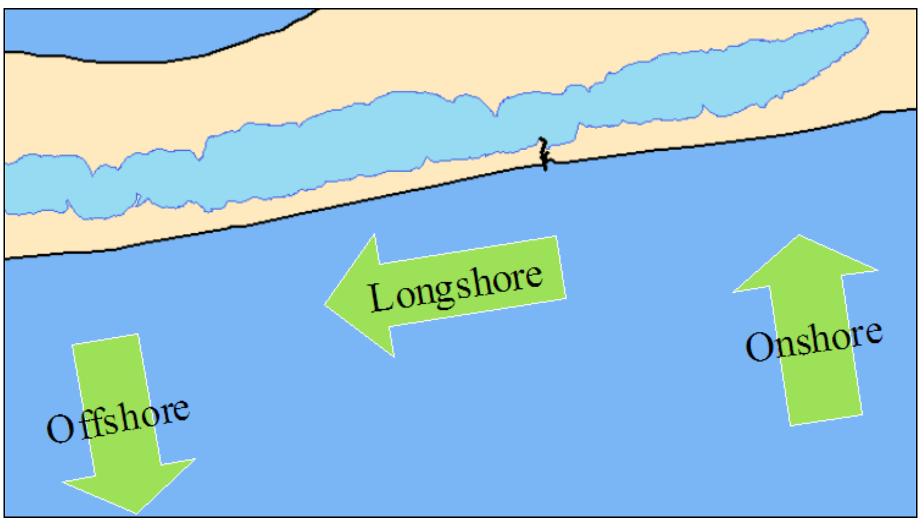

Figure 7

Longshore currents dominate and travel parallel to the coast (Huggett, 2003). They are the currents generated by obliquely approaching waves that run up the shore in the direction of wave propagation but move down the steepest slope, perpendicular to the shoreline. The parabolic path creates an overall movement along the shore. Longshore currents are confined to the surf zone, with a seaward boundary at the breaker line and a landward boundary at the shoreline. The

greatest velocities occur near the middle: normally a few centimeters per second, but reaching speeds of more than a meter per second in storm conditions. The net removal of material from a stretch of coast by longshore currents may result in coastal erosion, while the net influx of sediment by longshore currents may cause coastal accretion (Masselink and Hughes, 2003). These morphological changes will continue until the beach is shaped in a way that waves only approach parallel to the shore and longshore transport ceases.

The influence of currents created by rising and falling tides is subtler, except near the mouth of tidal inlets. A tidal inlet is a restricted, relatively narrow channel developed across a barrier where tidal currents are accelerated (Isla, 1995). They maintain a passageway between open waters like oceans and gulfs to confined waters like bays, lagoons, and estuaries. Tidal currents increase at the inlet mouth during flood tides when the water level of the ocean rises faster than that inside the inlet, creating a water surface slope that forces water into the inlet. Similarly, during ebb tides the water level of the ocean falls faster than that inside the inlet, creating currents exit the tidal inlet in a jet-like fashion. The volume of water moving through a tidal inlet is termed the tidal prism, and is closely related to the cross-sectional area. If the inlet size decreases, flow velocity increases and sediments within the inlet will be removed. If inlet size increases, flow velocity decreases and sediments will be deposited in the inlet. If the inlet shoals to the point of instability it will close. The flood tides carry sediment that was entrained primarily by wave currents, and they settle inside the inlet and embayed waters during slack high tide. Considerably higher velocities are required to re-entrain the sediments during ebb tides, resulting in a net landward flux (Woodroffe, 2003). The sediments deposited landward of the inlet form a flood-tidal delta and those deposited on the seaward side form an ebb-tidal delta.

Tidal inlets are not only responsible for the temporary loss of sediments during a tidal cycle, but also for longer-term interruption of longshore transport along the coast, affecting the position and mechanisms of sediment transfer along the shoreline (Nordstrom, 1987). Tidal inlets migrate when longshore transport adds sediment predominantly to the updrift side of the inlet and erodes it from the other. The migration is usually in the direction of transport. If the inlet is stable of the long term, then the beach and inlet have reached a form of equilibrium that allows for sediment bypassing (Davis and Fitzgerald, 2004).

The relationship between the cross-sectional area of tidal inlets and their tidal prism possesses considerable variability, largely because many inlets are controlled by physical structures, like jetties. Jetties are walls built to line the banks of tidal inlets to stabilize the waterway for navigation. The jetties extend into the sea, interrupting longshore transport, and promote deposition on the updrift side and erosion on the downdrift side (Figure 8). Also, jettied inlets continue to shoal and require dredging to maintain adequate depths. The dredged sediments are often deposited on the downdrift side of the inlet as nourishment projects to mitigate erosion.

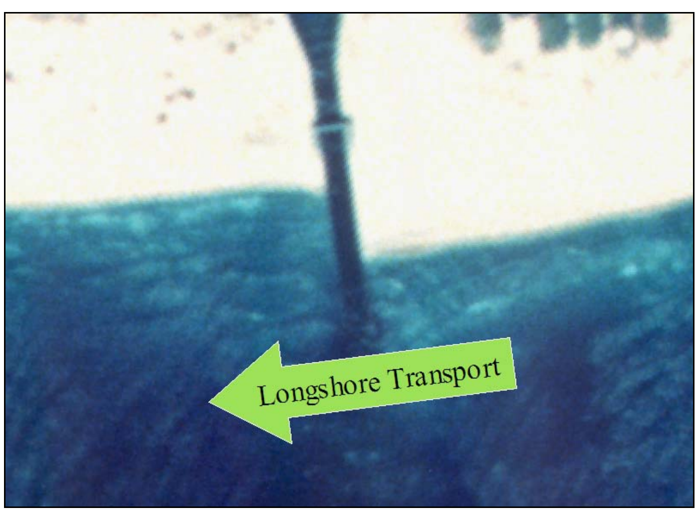

Figure 8 (Little Lagoon Pass, 1989)

Nourished beaches are built into a short-term state of disequilibrium that is smoothed out by surf-zone processes and longshore currents in the months after emplacement (Walton, 1994; Larson et al., 1999). Therefore, the deposited sediments are often rapidly eroded and need regular replenishing; often sourced by dredging coastal waters (Masselink and Hughes, 2003). Typically, the size of the sand used for nourishment must be equal to or somewhat coarser than that of local sediments to create a steeper profile and minimize rapid sediment loss offshore (Dean and Yoo, 1992; Stive et al., 1991). Like other forms of coastal protection, nourishment projects only treat the symptoms of coastal erosion, and as such are not a long-term solution. However, it is often the preferred method because it is relatively cost efficient and appears more natural.

Not only do tidal inlets accommodate navigation, but they are also conduits through which nutrients are exchanged between confined and open waters. In many lagoons, tidal inlets maintain salinities, temperatures, and nutrient levels. Coastal lagoons are impounded water bodies that represent an extreme form of barrier estuary (Cooper, 1994; Isla, 1995). Typical coastal processes such as tides and waves are not prevalent in lagoons, except near tidal inlets (Davis and Fitzgerald, 2004). They are often shallow and elongated, parallel to the coast, and seldom more than a kilometer wide. Because of their shape and confinement, often the only circulation within a lagoon is generated by wind waves formed over a limited fetch. On a geological time scale, lagoons are short-lived features controlled by sea level and climate (Woodroffe, 2003). Many coastal lagoons are not in equilibrium because they area subject to barrier transgression, relative sea-level change, and input of sediment from seaward and landward sources (Nichols, 1989).

DATA & METHODS

Three types of data were used in this study. First, digital vector shorelines (DVS) were downloaded from the National Ocean Service (NOS) Data Explorer website at http://www.ngs.noaa.gov/newsys_ims/shoreline/index.cfm. The years downloaded were 1917, 1934, 1958, and 1981. However, the 1934 and 1958 digital vector shorelines only covered approximately half of the study area and therefore were used only for reference, not measuring change. The 1917 vector shoreline did not include Little Lagoon and could only be used for measuring change along the gulf shoreline. The 1981 vector shoreline completely covered the study area.

The aerial photography used in this study was collected from a variety of sources (Table 4). Digital Orthophoto Quarter Quadrangles (DOQQs) were ordered from the United States Geological Survey (USGS) Earth Explorer website at http://edcsns17.cr.usgs.gov/EarthExplorer, and received on disk. High resolution (21-micron) scans of 1979 and 1989 color infrared photography (CIR) were also ordered through Earth Explorer and received on disk.

Summary of Aerial Photographs

Year	Type	Scale/Res	Source
1940	BW photo mosaics	Unknown	GSA
1949	BW photo mosaics	Unknown	GSA
1955	BW 9x9" paper prints	1:20,000	USDA
1960	BW 9x9" paper prints	1:20,000	USDA
1970	BW 9x9" paper prints	1:20,000	USA
1974	BW 9x9" paper prints	1:40,000	USDA
1979	CIR Hi-Res scans	1:65,000	USGS
1981	CIR 9x9" paper prints	1:60,000	USDA
1986	CIR 9x9" paper prints	1:60,000	USDA
1989	CIR Hi-Res scans	1:65,000	USGS
1992	BW 9x9" paper prints	1:40,000	USDA
1997	BW DOQQs	1m res	USGS
2004	Color images	Unknown	NOAA
2005	Color images	Unknown	NOAA

Table 4

Paper prints were ordered from the United States Department of Agriculture's (USDA) Aerial Photography Field Office. Black and white 9x9" prints were ordered for 1955, 1960, 1974, and 1992. CIR 9x9" paper prints were ordered for 1981 and 1986.

Post-Hurricane Ivan photos were downloaded from the National Oceanographic and Atmospheric Administration (NOAA) website at http://alt.ngs.noaa.gov/ivan. The photos were taken the day after Hurricane Ivan made landfall on the study area on September 16, 2004, but they were not used for measuring change because of the significant impacts major storms can have on coastal geomorphology. However, because Little Lagoon does not have strong currents or circulation, sediment deposited after major storms in the form of overwash fans tends to remain and therefore the 2004 post-Ivan photos were used to measure some change on Little Lagoon's shoreline. Post-Hurricane Katrina photos were also downloaded from NOAA, but they did not completely cover the study area and were only used for reference.

Black and white aerial photos were scanned at the University of South Alabama's (USA) Engineering Department for 1970, and used to measure change. USA's Engineering Department also houses aerial photos taken by the Alabama Department of Environmental Management (ADEM) every September since 1992, but because they did not cover Little Lagoon they were not used in this study. Photomosaics were scanned at the Geological Survey of Alabama for 1940 and 1949, but were used only for reference.

Finally, a LIDAR derived vector shoreline from 2001 was downloaded from the USGS's Coastal and Marine Geology Program at http://pubs.usgs.gov/of/2004/1089/gis-data.html. Also downloaded from this site were transects, a baseline, and a vector representing nourishment projects, created by Miller *et al*. (2004).

ArcMap 9.1 was the Geographic Information System (GIS) used in this study. GIS-based analyses should provide more accurate estimates of shoreline change than previous research studies because of the limitations in methods and equipment used in older studies (Langley et al., 2003). The DOQQs were loaded first. Because they were already spatially referenced to Universal Transmercator (UTM) North American Datum (NAD) 83, Zone 16, that was the projection used for all other data.

Paper prints were scanned and saved as a tagged image file formats (TIFF). All TIFFs, including the Hi-Res scans obtained from the USGS, were added to ArcMap and georeferenced to the DOQQs using the Georeferencing Tools. Sixteen ground control points (GCPs) were used in all but the 2004 post-Ivan photos. For those, only three GCPs were needed to ensure a good fit because of their large scale. With a first order polynomial transformation for the post-Ivan photos and a third order for all others, the total root mean square (rms) error was less than 1.5m for every photo. That's well within the 0.5 to 3.0m rms error typical of shoreline change studies (Fletcher *et al*., 2003).

The next step was to determine a shoreline reference feature upon which to base measurements. This study used the high-water line (HWL) because it was easily distinguishable on all photos as a wet/dry line (Figure 9). Also, the HWL is the legal shoreline of the United

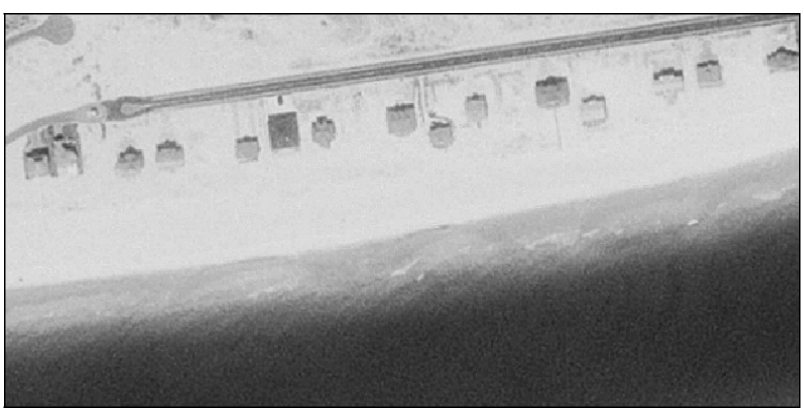

Figure 9 (Example of distinguishable HWL)

States, represented in NOAA nautical charts, and is considered the most consistent reference feature (Parker, 2003).

I digitized the HWL manually by creating a new line feature in ArcMap. By zooming into a 1:1000 scale, I was able to follow contours along the wet/dry line by adding vertices at each change in direction. Because the contrast between wet and dry sand varied over distance, more automated methods like assigning unique colors to each of the 256 values in the black and white photos failed since no single spectral value appeared to follow the HWL consistently. A supervised classification of the CIR images also failed to follow the HWL consistently.

In ArcMap, I added the baseline downloaded from the USGS upon which to base all gulf shoreline measurements. The baseline is over water, parallel with the general shape of the beach. Next I added the transects downloaded from USGS. The transects are spaced 50 meters apart perpendicular to the baseline, covering about 12.7km of shoreline south of Little Lagoon. The transects are numbered from 1 to 254 from east to west, following the direction of longshore transport (Figure 10). I used the Intersection Tool in ArcMap to create a point where transects and digitized shorelines intersected. However, the Intersection Tool had some limitations in that it would create more than one point on a transect if the shoreline crossed the transect more than

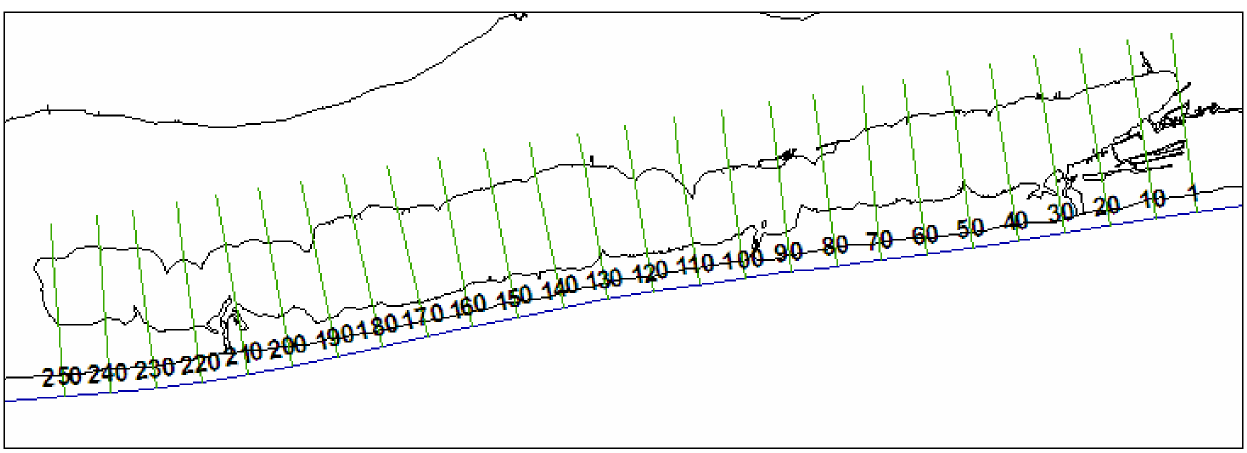

Figure 10 (Transect numbering)

once, which was often the case near tidal inlets. Also, no point was created where the shoreline did not cross a transect, which occurred when the transect happened to lie within a tidal inlet. Some manipulation was required to ensure that only one point existed along each transect, and that the points were in the same order as the numbered transects. The points could then be spatially joined to the baseline to create a field that calculated the shortest distance from each point to the baseline; the shortest distance is perpendicular to the baseline along the transect. The process was repeated for Little Lagoon's southern shoreline, but only to facilitate a correlation analysis. Figure 11 shows an example of the baseline, transects, and intersected points in ArcMap.

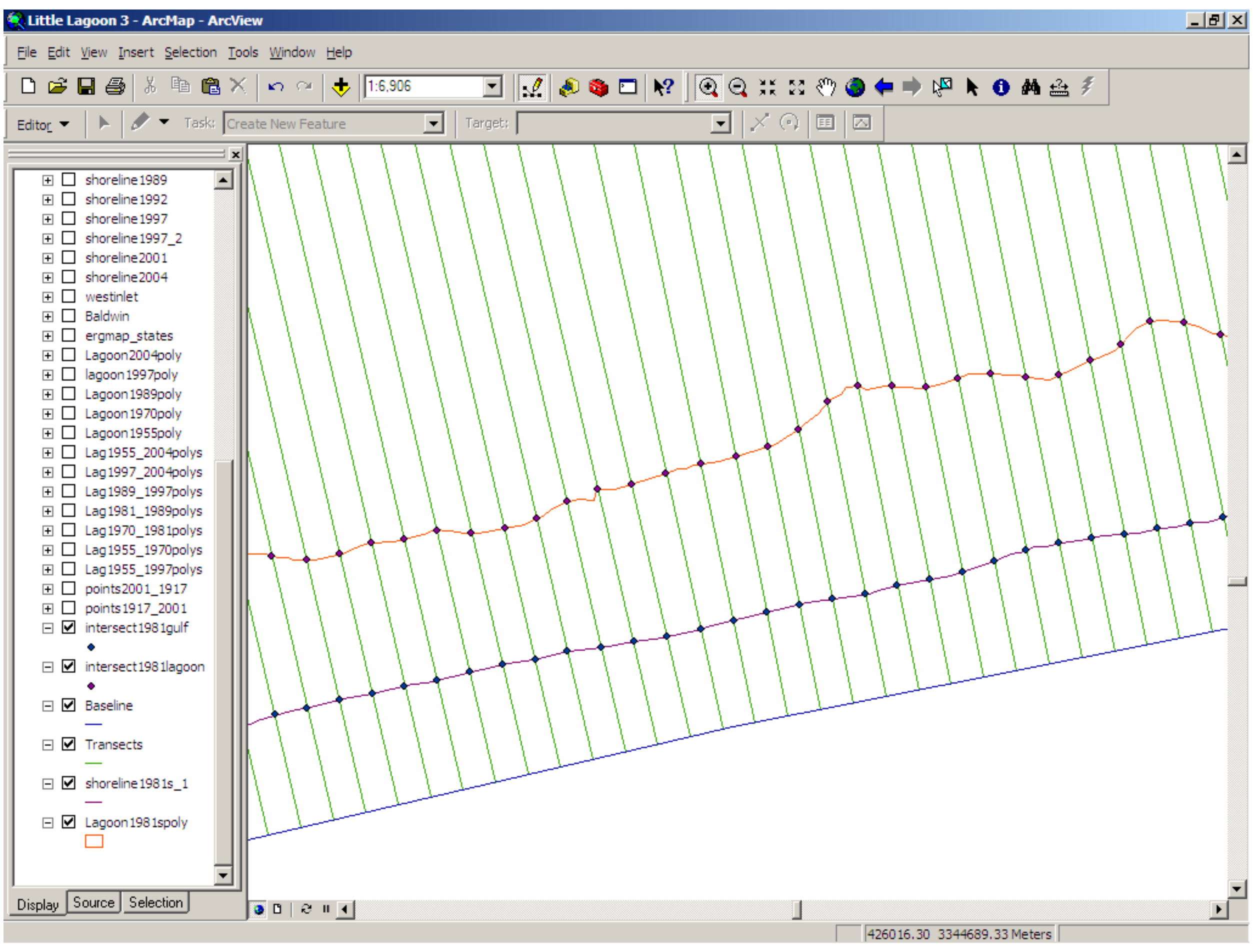

Figure 11 (Baseline, transects, shorelines, and intersection points in ArcMap)

The distance field for each year group was then copied into an Excel spreadsheet. The amount of change along each transect between years was calculated by subtracting the distances of one year group from the distances of another year group. Then graphs like the one in Figure 12 were created with exaggerated scales to highlight areas of significant change.

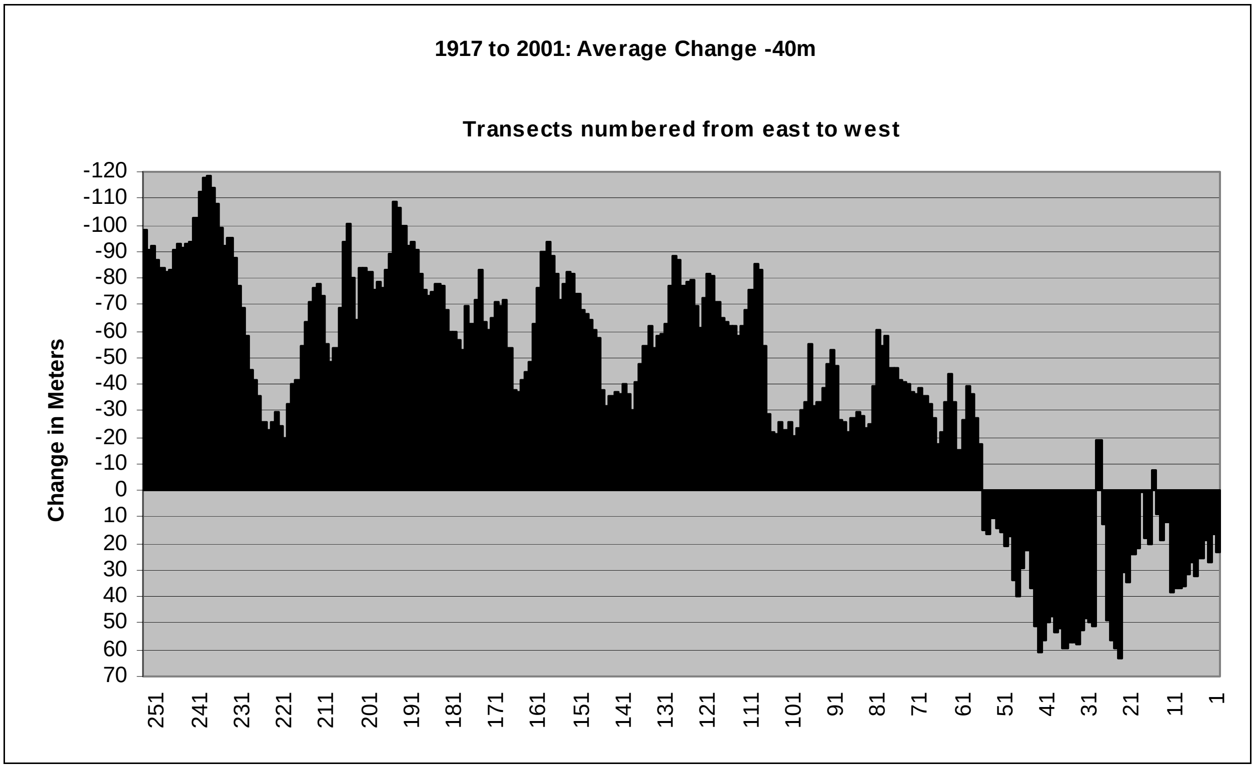

Figure 12 (Gulf shoreline change from 1917 to 2001)

The change on Little Lagoon's shoreline was calculated differently. Because the lagoon shoreline has steep curves in many places, linear transects will exaggerate the amount of change significantly even with the slightest error associated with the georeferencing process. Therefore the lagoon shoreline was digitized into a polygon shapefile. By combining two polygons from different years using the Construct Features tool in ArcMap, I was able to create polygons

representing the areas of change between years. This tool also provides a shape area for the new polygons, as well as a shape length. By dividing the shape area by half the shape length, the average accretion or erosion can be gained along linear stretches of Little Lagoon's shoreline. Because the number of polygons for each new shapefile ranges from 446 to 557, I will not attempt to explain every change but only the areas of greatest change. Figure 13 shows an example of the new polygons with the area of greatest change highlighted, and the attribute table.

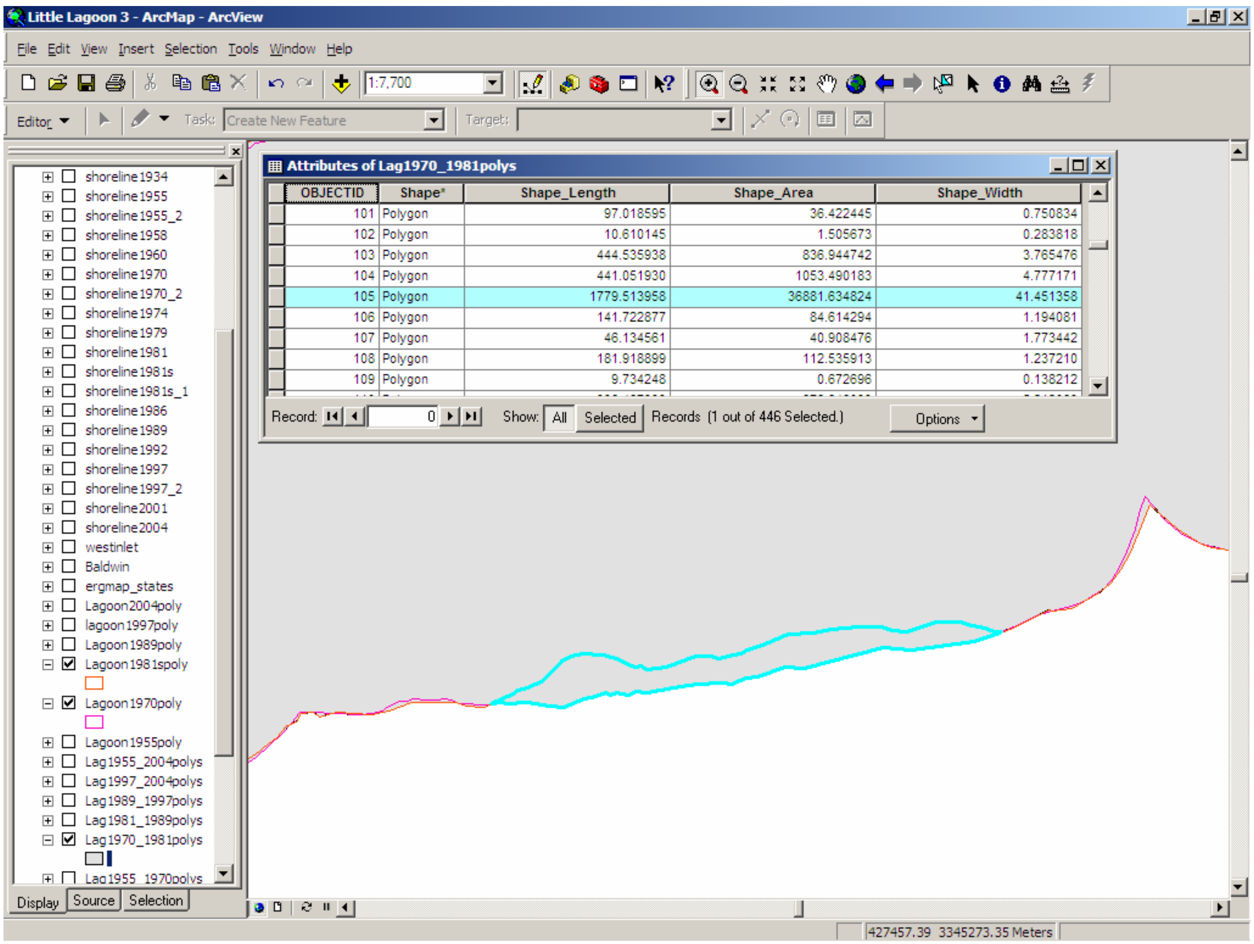

Figure 13 (Example of lagoon shoreline change in a polygon shapefile)

A correlation analysis was conducted to determine if and where relationships existed between areas of change on the gulf shoreline and Little Lagoon's southern shoreline. I conducted the correlation analysis for all 254 transects to represent the overall relationship.

Then I conducted the analysis for 1km lengths, starting at transect number 21. For example, an analysis was conducted for transects 1 through 21, then 2 through 22, 3 through 23, and so on. I used a two-tailed test with a significance, α, of 0.01. Coefficients of 0.549 (or –0.549) or greater are critical values of Pearson's *r* for testing the significance (Kachigan, 1986). Areas of significant correlation are discussed in the results.

Sources of Error

The resolution of the aerial photos used can cause error when attempting to delineate the shoreline. While there is no absolute value for the resolution of the photographs used in this study, Campbell (2002) points out that the resolution needed depends on the application. For example, the low-altitude aerial photos taken by ADEM are of greater resolution than the higher-altitude aerial photos used in this study, but they did not include Little Lagoon and therefore were of no use in this research. Also, the georeferencing process may have been completed with an rms error of less than 1.5 meters, but that doesn't ensure that any one feature is actually within 1.5 meters of where it is depicted (Fletcher *et al*., 2003).

The use of a non-morphologic feature to delineate the shoreline also creates some error. The HWL has been proven to have shortcomings because of the effects of numerous influences like winds, wave action, temperature, and salinity to name only a few (Parker, 2003). Plus, the HWL only approximates the Mean HWL (MHWL) used by the National Ocean Service and many other agencies to define the land/sea boundary (Graham *et al*., 2003). The strength of the MHWL is that it is an average of 19 years of HWLs in order to mitigate the influence of tides. The photos used in this study were not tide-coordinated, so the stage of the tide creates another source of error (Hess, 2003). However, many studies have concluded that the difference

between the HWL and the MHWL is either insignificant or acceptable error (McBeth, 1956; Dolan *et al*., 1980; Crowell *et al*., 1991). Despite its shortcomings, the HWL is still the most consistent way to represent shorelines (Parker, 2003).

The sampling technique used may include error. Much of this study is based on transects spaced 50-meters apart, perpendicular to the general shape of the shoreline and mostly parallel to one another. The correlation analysis conducted in this study was tested on three separate areas of shoreline for five different year groups using 10-, 25-, and 50-meter spacing. The values obtained were almost identical, proving that 50-meter spacing captures as much signal, and noise, as smaller spacing, and is therefore acceptable.

Errors considered, the results are still accurate enough to determine where erosional or accretional trends existed between year groups and to estimate average change.

RESULTS & DISCUSSION

Shoreline change depends on many factors, such as wave and current regime, sea-level change, storm frequency, sediment supply, and human activities like large-scale civil engineering projects (Gonzalez, *et al.*, 1997). Between 1917 and 2001, the gulf shoreline had an average change of –40m over the 254 transects. That is almost half of a meter of erosion per year for the entire 12.7km gulf shoreline study area. While this may seem like a small amount of change when compared to similar studies, an examination of the graphic representation (Figure 6) shows that some portions of beach eroded almost 120 meters while other portions accreted more than 60 meters. Also, distinct spikes or reverses in trends exist near transects 27, 97, and 213. The spikes are easy to explain because they are where inlets have closed and opened during the study period, but the areas of accretion and erosion are harder to explain at this temporal scale. For example, the average change for the years 1917 to 1955 is also –40 meters, but that certainly doesn't mean that no change has occurred since 1955. On the contrary, some of the most dramatic changes have occurred in the last 50 years. To better understand the dynamics, we need to break the temporal scale into periods that make use of the data available and make sense for what was actually occurring in the study area.

The results are analyzed in six groups. The years 1917 through 1955 represent the first group. This was a period of transition when the natural inlet moved from the eastern end of the lagoon to the western end. Because the 1917 DVS did not include Little Lagoon, correlation and lagoon shoreline change for the period 1917 to 1955 will not be discussed. The second group spans the years 1955 through 1970; the natural tidal inlet was located near the western end of the lagoon throughout this time period. The years between 1970 and 1981 mark another period of

transition when the natural inlet in the west closed and a natural inlet opened near the center of the lagoon. The HWL represented in the 1981 shoreline is prior to the construction of jetties to stabilize the natural tidal inlet that same year, an engineering project known as Little Lagoon Pass. The fourth group spans from 1981 to 1989 and shows well the change associated with Little Lagoon Pass, and ends at a time described by Smith (1991) as near equilibrium. The years between 1989 and 1997 represent the fifth group and include changes to The Pass, such as the shortening of the jetties and beach nourishment projects. The final group discussed actually separates the gulf shoreline and lagoon shoreline because of the data used. In the final group the shoreline change will be analyzed between 1997 and 2001, but because the LIDAR data taken in 2001 did not include Little Lagoon this period will only focus on gulf shoreline change. However, the 2004 photos taken immediately after Hurricane Ivan reveal some significant changes to the lagoon shoreline that will be discussed separately in a 1997 to 2004 group.

1917 to 1955

The first time period to be examined is from 1917 to 1955. This is the largest time period covered in the study and is a transitional period in which natural inlets close and open elsewhere. The 1917 DVS shows only one inlet to Little Lagoon, approximately 1.5km from the eastern end of the lagoon near transect 27. In the 1934 DVS the inlet is no longer there, but because the data is incomplete it is impossible to say if an inlet was open in the western half of the lagoon at that time. However, the 1940 and 1949 photo mosaics show now clear-cut inlet. In the 1955 aerial photos a natural inlet is clearly distinguishable approximately 2km from the western end of the lagoon near transect 213, which is where the inlet was depicted in most historical maps dating back to 1804.

The average change to the gulf shoreline over all 254 transects during this time period is –40 meters, or –1.05 meters per year (Figure 14). However there are two areas that depart from this erosional trend. One is immediately downdrift of the 1917 eastern inlet at transect 27, and the other is downdrift of the 1955 western inlet at transect 213. The accretion downdrift of the eastern inlet at transect 27 is because sediments are no longer being lost to the lagoon during flood tides. The area resistant to erosion downdrift of the western inlet at transect 213 is an area of equilibrium, described by Masselink and Hughes (2003), where the morphology is able to dissipate incoming energy and resist morphological change.

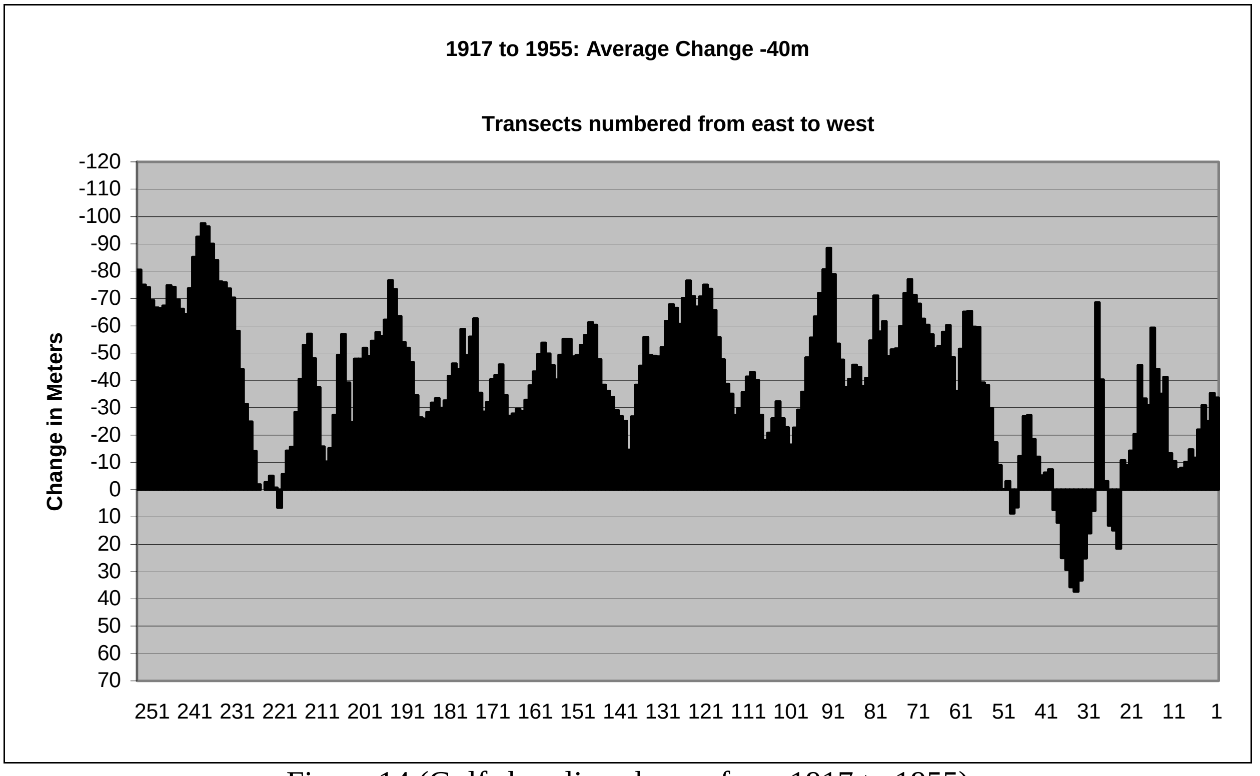

Figure 14 (Gulf shoreline change from 1917 to 1955)

1955 to 1970

The second time period to be examined is from 1955 to 1970. The western natural inlet remained opened throughout this period, though its shape did change over time. The average change of all 254 transects was –10 meters on the gulf shoreline, approximately -0.67 meters per year. In Figure 15, a noticeable erosional trend exists downdrift of transect 97 for about 1km.

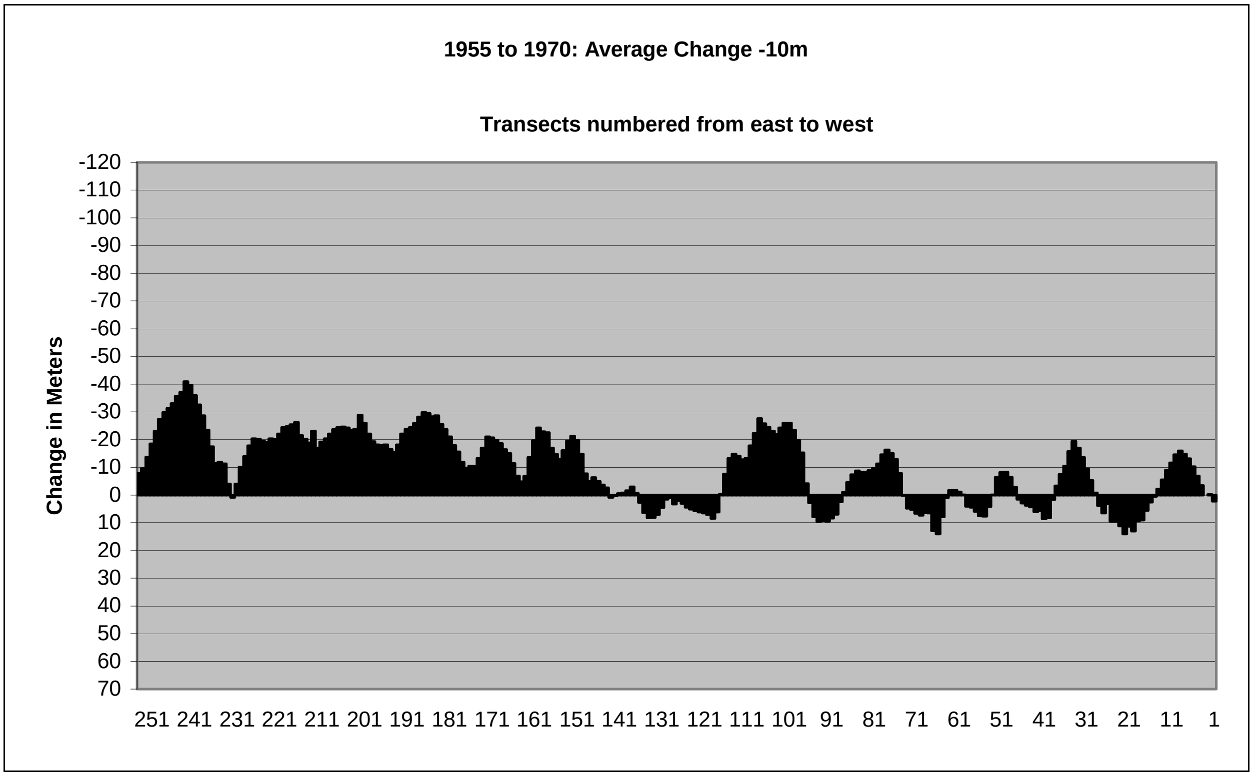

Figure 15 (Gulf shoreline change from 1955 to 1970)

Transect 97 is the location of the central inlet in Figure 2. In the aerial photographs of this period, the area does appear to accommodate interaction between the Gulf of Mexico and Little Lagoon, probably during higher high tides and storm tides (Figure 16). Sediment was lost to the lagoon during flood tides, but not returned to the gulf during ebb tides. Further downdrift exists an erosional trend that stretches from about transect 144 through most of the remainder of the

study area, spanning almost 5km. Again, sediment was probably being lost to the lagoon during higher high tides. Figure 17 is centered on transect 144 and clearly shows the evidence of gulf and lagoon interaction. Near transect 232 is an area that seems resistant to the erosional trend. It is about 1km downdrift of the inlet at transect 213 and is an area of equilibrium, described by Masselink and Hughes (2003), where the morphology is able to dissipate incoming energy and resist morphological change.

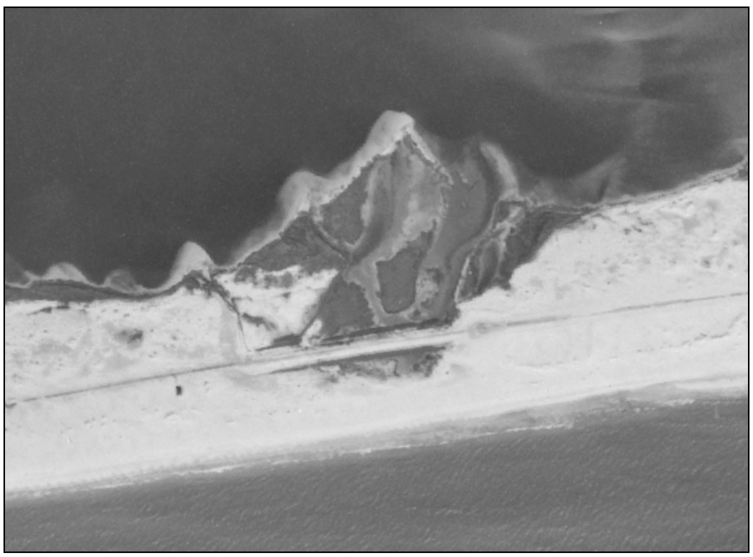

Figure 16 (Photo of central inlet at transect 97 in 1955)

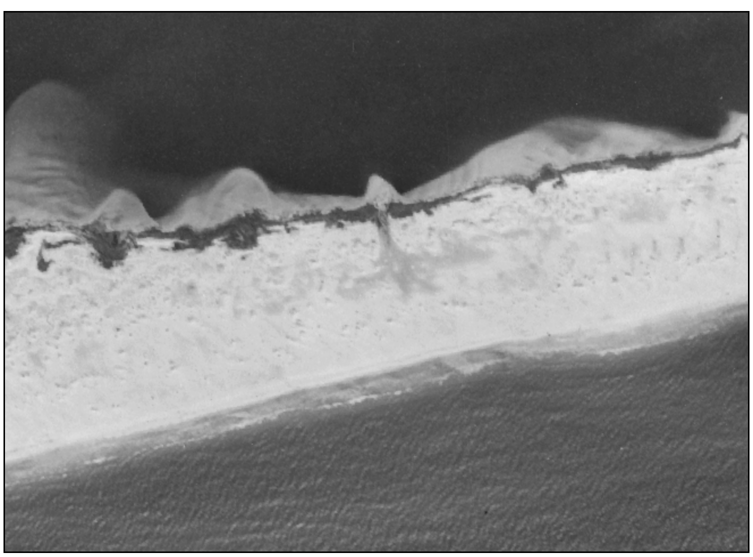

Figure 17 (Photo of area near transect 144 in 1955)

Between 1955 and 1970, Little Lagoon shrank 7.7km², from 10,285.9 to 10,278.2km². That's 513m² per year. The two largest areas of change are discussed. First, the area near the natural inlet that existed between 1955 and 1970 accreted 11km² (Figure 18). That is 733m² per

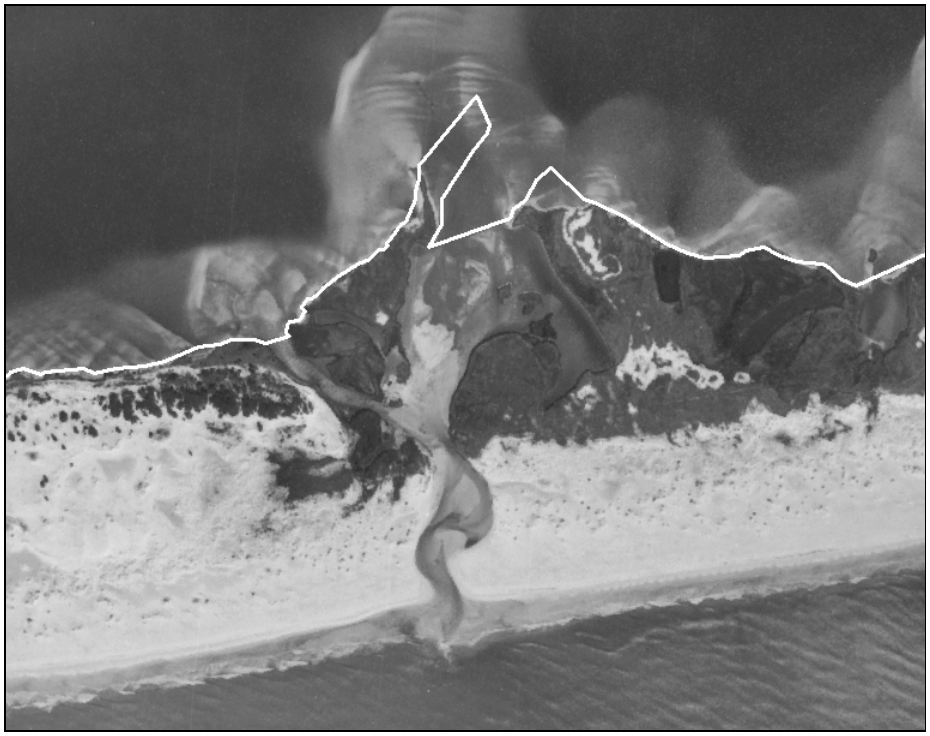
Figure 18 (Western inlet in 1955 overlaid with 1970 shoreline in white)

year. When a new inlet is cut, the lagoon that it connects will experience change (Kraus, 2005). This accretion was in the form of a flood delta, as floodtides carried sediments into the lagoon that were deposited as the rate of discharge was reduced. Little change has occurred in the area since the 1970 photos, indicating that little to no tidal waters have interacted there since the inlet's closure sometime between 1970 and 1974. An area of significant erosion existed on Little Lagoon's southern shoreline between transects 187 and 194 (Figure 19). During this time 9.3km² of shoreline were eroded. That's 620 square meters per year. By dividing the polygon shape area by half the shape length, I calculated an average erosion of almost 24 meters linearly.

While there is no readily apparent cause of the erosion, it is possible that as more homes were developed the marshy area seen in 1960 photos was removed because it is not seen in 1970 photos when the first houses arrive in the area.

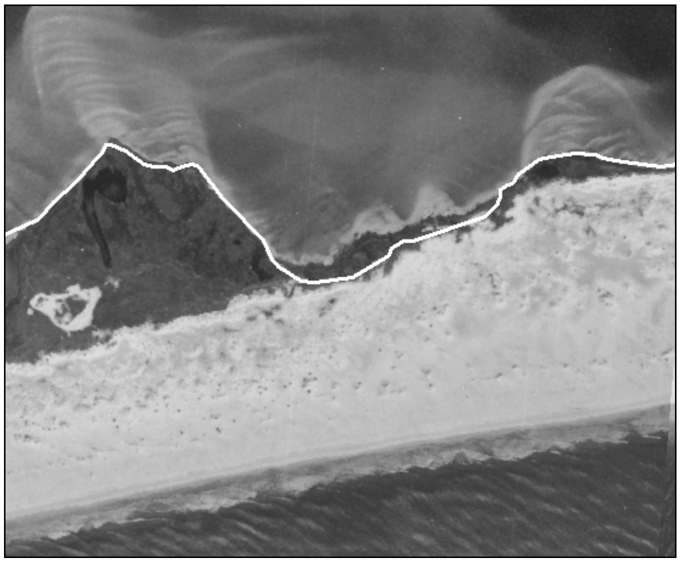

Figure 19 (1955 photos of area that later eroded overlaid with 1970 shoreline in white)

The overall correlation for this time period is a nonexistent -0.031. Between 1955 and 1970, the gulf shoreline eroded an average of –10m over the 254 transects, while the lagoon accreted an average of +2m. Despite the lack of correlation, three areas of strong relationships do exist within the 12.7km study area (Figure 20). Moving east to west, the first area of significant correlation exists between transects 17 and 42, for 1.2km. Here, one-kilometer correlation coefficients range from –0.559 to –0.633. This area corresponds with the location of a natural tidal inlet near transect 27 that was open in 1917, but closed some time before 1950. While the gulf shoreline accreted an average of 1m over the 25 transects, the lagoon shoreline showed no change. However those numbers don't tell the entire story. Updrift of the inlet, the

gulf shoreline accreted over all 11 transects with values ranging from +3m to +14m for an average of 9m, but the lagoon shoreline eroded on 8 out of the 11 transects with values ranging from +4m to –32m for an average of –8m. Conversely, downdrift of the inlet, the gulf shoreline eroded on 10 of 15 transects with values ranging from +9m to –19m for an average of –5m, but the lagoon shoreline accreted on 11 of 15 transects with values ranging from –1m to +26m for an average of +6m. The negative correlation reflects the inverse relationship between the gulf and lagoon shorelines: where the gulf side accreted, the lagoon side eroded, and vice versa. Figure 21a shows that the relationship is negative curvilinear, concave downward.

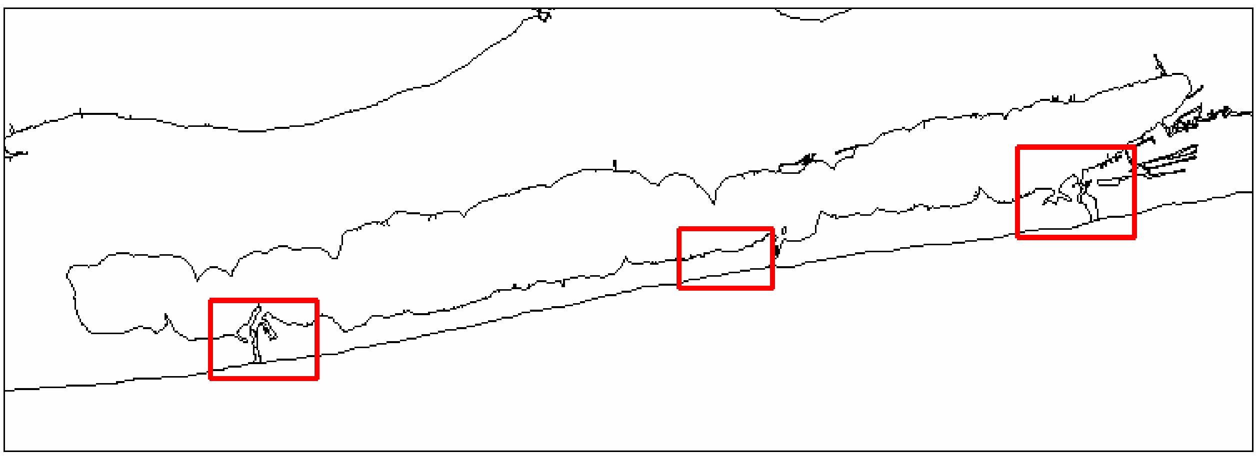

Figure 20 (Areas of significant correlation for changes between 1955 and 1970)

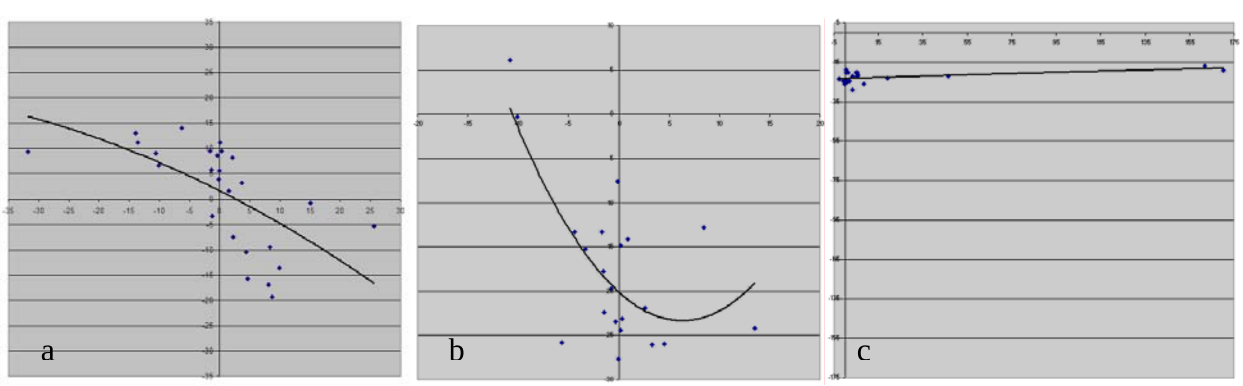

Figure 21

The second area occurs downdrift of transect 97 for 1km, between transects 98 and 118. This is interesting because a natural inlet opens at transect 97 sometime between 1974 and 1976, but obviously some interaction between the Gulf of Mexico and Little Lagoon was occurring prior to that. Over the 1km, the gulf shoreline eroded –18m, and the lagoon shoreline eroded less than –1m. The correlation coefficient is –0.562. The gulf shoreline eroded on all but one of the 21 transects with values ranging from +6m to –28m, while the lagoon shoreline eroded on 12 of 21 transects with values ranging from –11m to +14m. Figure 21b shows the relationship is non-monotonic, concave upward, meaning that the two variables are positively related within a certain range of values, and negatively related in another range (Kachigan, 1986).

The third area to be discussed for this time period exists between transects 200 and 223, total 1,150m. Correlation coefficients range from –0.566 to –0.598. The gulf shoreline eroded over all 24 transects with values ranging from –17m to –29m for an average of –23m, but the lagoon shoreline accreted over 20 of the 24 transects with values ranging from –3m to +170m for an average of +18m. This area is almost centered about the natural inlet that was open between 1955 and 1970 near transect 213. The negative correlation reflects the inverse relationship between the gulf and lagoon shorelines: where the gulf eroded, the lagoon accreted. Figure 21c shows a positive linear relationship, but is exaggerated because two values are outliers.

1970 to 1981

The period from 1970 to 1981 is another transitional period. Sometime before 1974, the western inlet closed leaving no clear-cut inlet to Little Lagoon, though the area around transect 97 does appear to have an ebb shoal present in the 1974 aerial photographs (Figure 22). Most

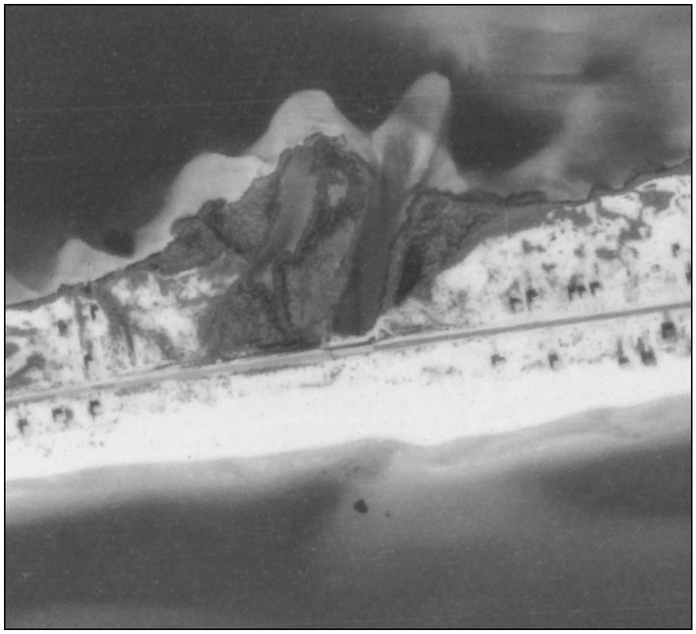

Figure 22 (Photo of central inlet in 1974)

likely, the gulf and lagoon did interact during higher high tides and storm tides. In 1976 USGS topographic quadrangles of the study area, a natural inlet does exist near transect 97. The 1979 and 1981 aerial photos, and the 1981 DVS show a natural inlet at that location.

When all 254 transects are averaged, less than 1m of change occurred on the gulf shoreline during this time period. But the graph (Figure 23) shows an erosional trend for the first 3km, from east to west. This time period coincides with significant coastal construction taking place in the city of Gulf Shores, including the construction of piers that may have forced some littoral drift sediments to be diverted offshore, causing erosion for a few kilometers. These sediments later returned with onshore flow, explaining the spotty accretional trend spanning much of the remaining transects. Also, a major hurricane impacted the area in 1979; that may have significantly altered the shore morphology to an extent that two years of normal conditions could not return the shore to its previous state.

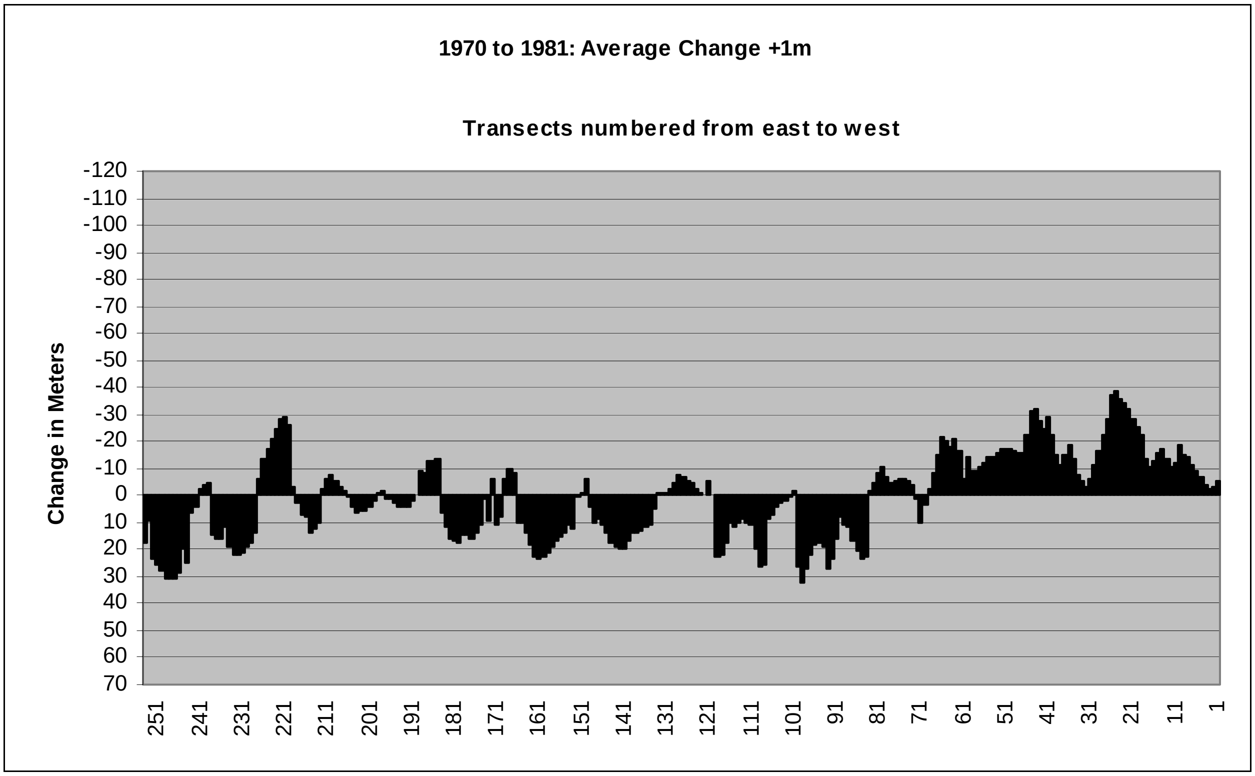

Figure 23 (Gulf shoreline change from 1970 to 1981)

Between 1970 and 1981, Little Lagoon lost another 41.6km² to reach a total area of 10,236.6km². That loss equates to 3,783m² per year. The most significant change occurred along a linear stretch of beach between transects 135 and 152 that accreted an average of over 41 meters (Figure 24). Careful inspection of the aerial photos revealed that this was not a slow process spanning 11 years, but a rapid accretion that occurred between 1974 and 1979. Most likely it is the resulting overwash fan from Hurricane Frederic in 1979, one of the most powerful storms to ever affect the study area, with storm surges between 10'and 12'. That single overwash fan comprises almost 37km² of sediment deposition onto Little Lagoon's southern shoreline. The 1979 photos were taken only a few weeks after Frederic made landfall, and the evidence of overwash is still apparent. Stallins and Parker (2003) observed that overwash disturbances affect feedbacks among vegetation, landforms, and sediment mobility, meaning that this single event had long-lasting effects.

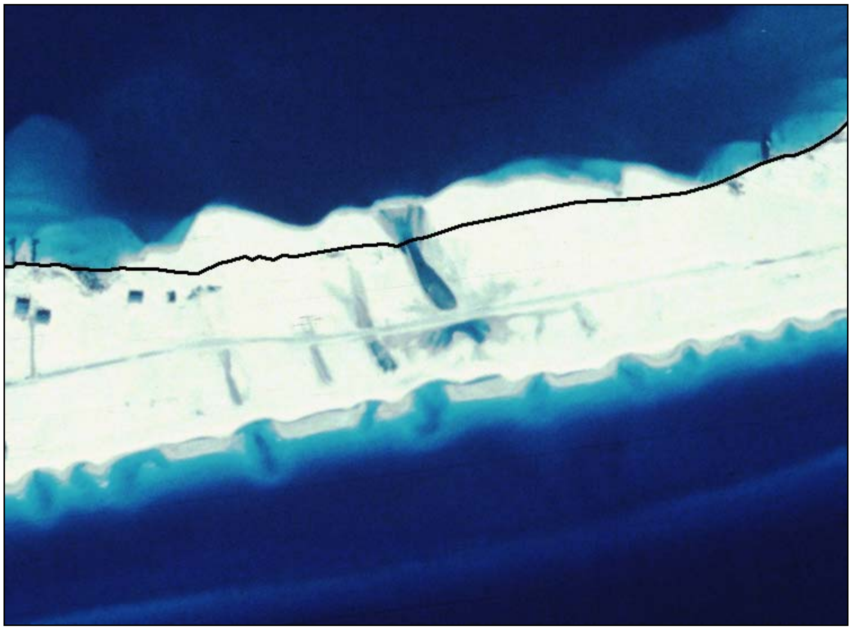

Figure 24 (1979 aerial photo overlaid with 1970 lagoon shoreline in black)

The second study period also has a very low correlation coefficient: +0.121. During this eleven-year period, the gulf and lagoon shorelines showed little overall change when averaged across the 254 transects, +1m and +3m respectively. However, two areas of significant correlation are worth mentioning (Figure 25). Between transects 84 and 124 the correlation coefficient ranged from –0.549 to –0.732. This correlation exists at the central inlet and for over one kilometer downdrift. Over the 2km, the gulf shoreline accreted on 35 of 41 transects with values ranging from –6m to +32m for an average of +13m, and the lagoon shoreline eroded on 35 of the 41 transects with values ranging from –12m to +18m for an average of –2m. The negative correlation reflects the inverse relationship between the gulf and lagoon shorelines. Figure 26a shows a non-monotonic, concave upward relationship.

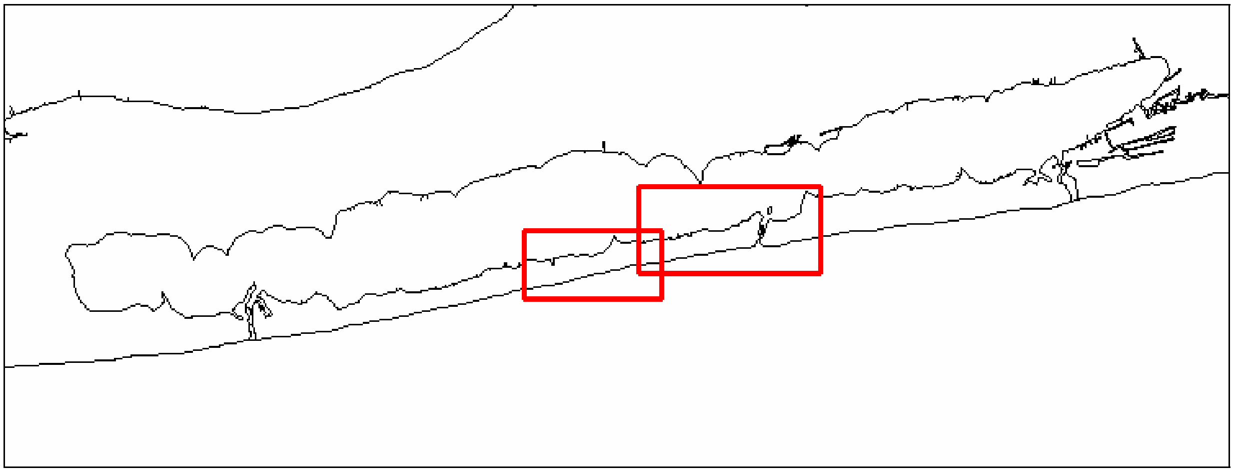

Figure 25 (Areas of significant correlation for changes between 1970 and 1981)

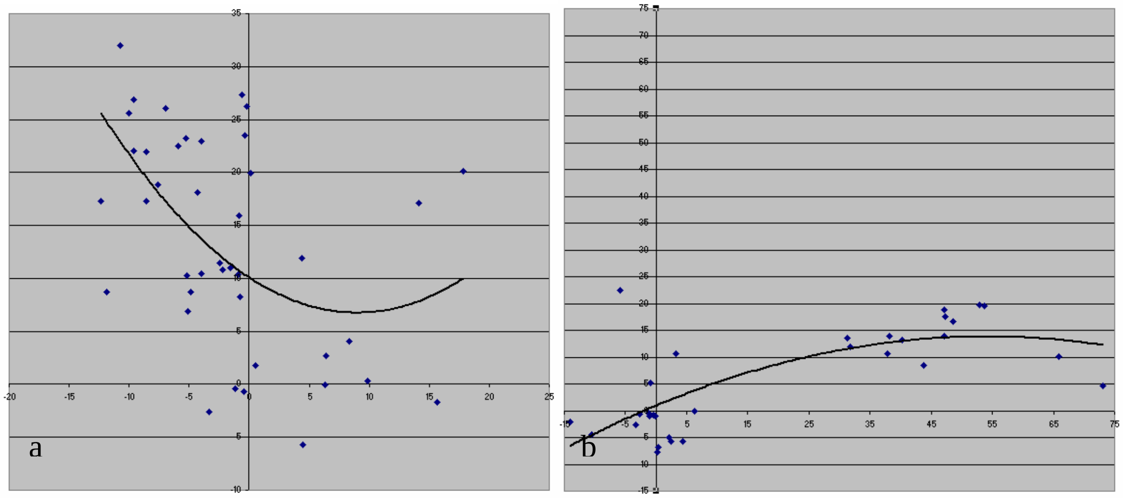

Figure 26

Strong correlation coefficients also exist between transects 120 and 150, ranging from +0.573 to +0.917. This area somewhat overlaps the previous, and coincidently occurs around a large overwash fan created by Hurricane Frederic in 1979. Here the gulf shoreline accreted on 16 of the 31 transects with values ranging from –8m to +23m for an average of +6m, and the lagoon shoreline accreted on 21 of the 31 transects with values ranging from –14m to +73m for an average of +21m. The positive correlation reflects the direct relationship between the gulf

and lagoon shorelines, both seemingly growing from the amount of sediment moved by Hurricane Frederic. Figure 26b shows a slight non-monotonic, concave downward relationship.

1981 to 1989

The fourth time period in this study is from 1981 to 1989. In 1981, the Alabama Highway Department constructed Little Lagoon Pass, two jetties to stabilize the natural inlet near transect 97. Coastal construction is usually established with and expectation for permanency, but the land-sea buffer is in dynamic equilibrium with natural forces and therefore susceptible to change (Smith, 1981). An obstruction to longshore drift, like a jetty, often triggers erosion downdrift of the obstruction (Orford, 1988). The initial erosional depression moves downdrift because the transport potential downdrift is always greater (Inman, 2003), which is why the erosion cut may be defined as “infinite” (Bruun, 1995). Subsequent deepening and steepening of the seafloor reduces the ability of beaches to accumulate sand by allowing for larger waves, creating greater erosion (Buijsman, 2003). Coastal engineers predicted that significant erosion would take place downdrift of the jetties (Douglas, 2002), but the project was carried out without a sand bypassing system. This study period ends in 1989, close to the time that Smith (1991) states that the area was approaching equilibrium. Although the average change over the 12.7 km study area during this short eight-year time period is a significant –12m, or –1.5m per year, some areas eroded much more than others (Figure 27). From transect 1 to transect 96, just prior to the eastern jetty, the average change was zero. From transect 98, just after the western jetty, to the end of the study area the average change was –20m, or –2.5m per year. However, the most significant erosion occurred within the first 2.5km following the western jetty: –31m, almost 4m per year.

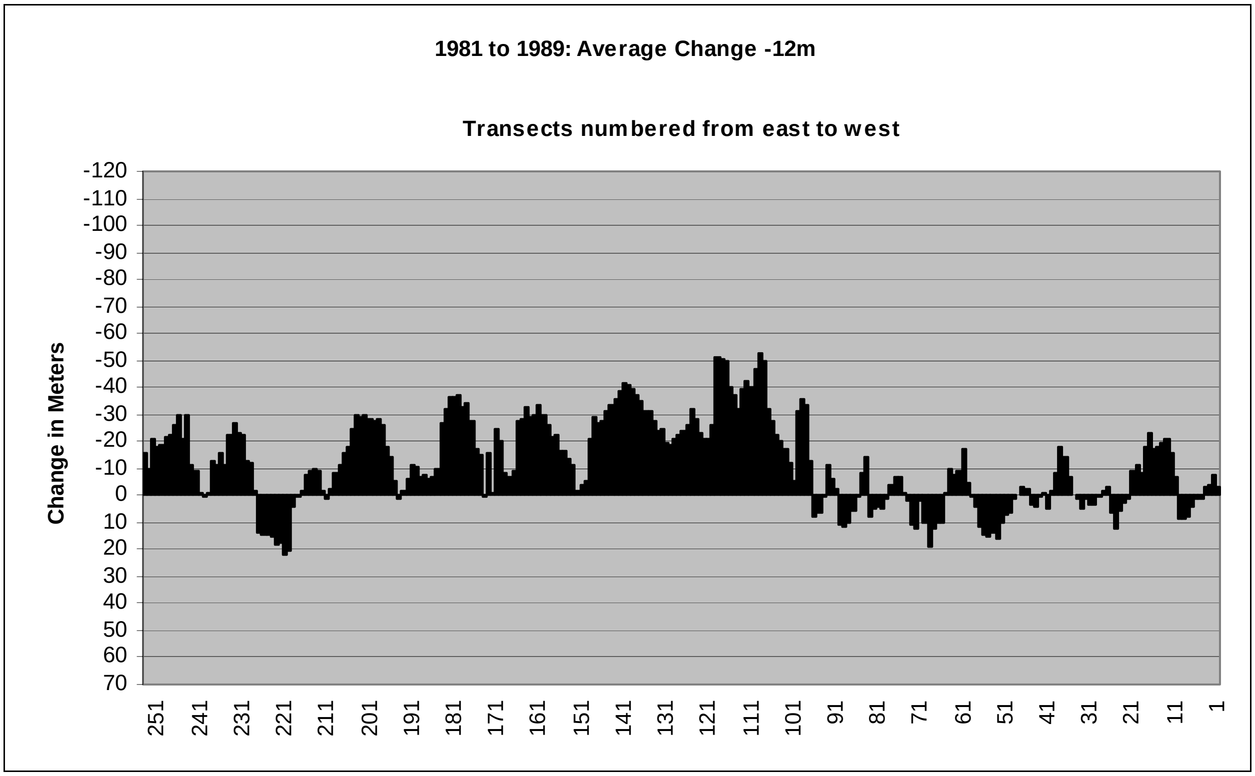

Figure 27 (Gulf shoreline change from 1981 to 1989)

Between 1981 and 1989, Little Lagoon continued to lose area from 10,236.6 to 10,227.9km², a total of 8.7km², or 1089m² per year. However, the most significant change was the accretion that occurred near Little Lagoon Pass (Figure 28). East of The Pass, the lagoon shoreline accreted 3,576m². When the shape area is divided by half the shape length, the area grew an average of over 8m linearly. The lagoon's southern shoreline east of the pass was not stabilized with seawalls, as was the west, and suffered from jet-like flows common with engineered tidal inlets (Hughes, 2000) that carried and deposited large amount of sediments. Immediately west of The Pass, the lagoon shoreline accreted 460m², or an average of 4m. However, "accreted" may not be the best description of what happened because the change simply reflects the placement of a seawall on the western side of The Pass. Another area of large

Figure 28 (1989 aerial photo overlaid with 1981 lagoon shoreline in blue)

change occurred near the overwash fan deposited by Hurricane Frederic. Between transects 141 and 150, the lagoon shoreline eroded 2,716m², about –6m linearly.

The correlation of the gulf and lagoon shorelines between 1981 and 1989 is a dismal –0.030, with the gulf shoreline eroding –12m and the lagoon's southern shoreline accreting just over +1m along the 254 transects. Not coincidentally, one area of significant correlation during this period is at Little Lagoon Pass (Figure 29). Between transects 81 and 107 the correlation ranges from +0.560 to +0.668. Over the 1.3km area, the gulf shoreline eroded on 16 of the 27 transects with values ranging from –35m to +11m for an average of –8m, while the lagoon shoreline accreted on 19 of the 27 transects with values between –7m and +16m for an average of +4m. However, updrift of The Pass the gulf shoreline accreted on 11 of the 16 transects with values ranging from –14m to +11m for an average of +2m, while the lagoon shoreline accreted on all but two transects with values from –2m to +16m for an average of +6m. Downdrift of

The Pass, the gulf shoreline eroded on all of the 11 transects with values ranging from –5m to –35m for an average of –23m, while the lagoon shoreline eroded on 6 of the 11 transects with values between –7m and +7m for an average of less than –1m of erosion. The positive correlation reflects the direct relationship between the gulf and lagoon shoreline at the engineered inlet: where the gulf shoreline accretes, so does the lagoon shoreline, and vice versa. Figure 30a shows a positive curvilinear, concave downward relationship.

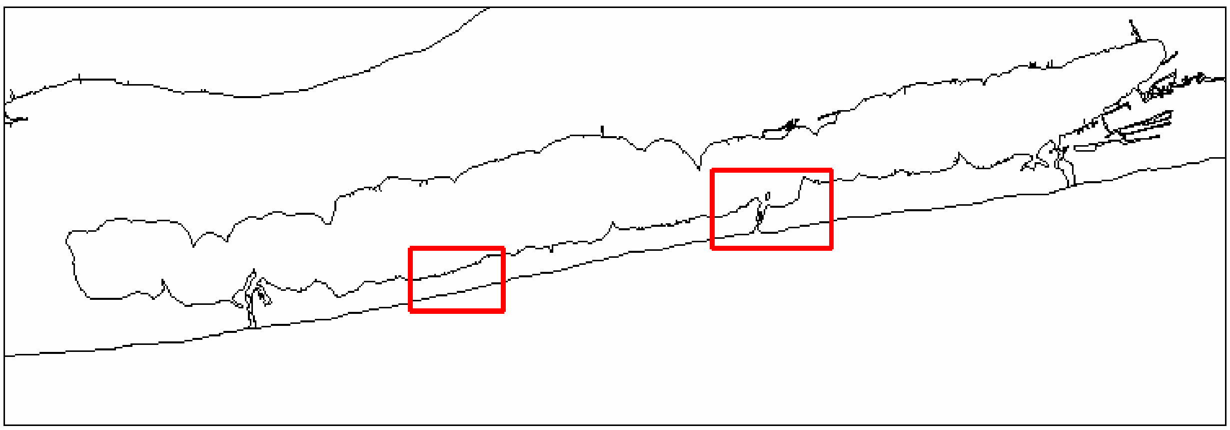

Figure 29 (Area of significant correlation for changes between 1981 and 1989)

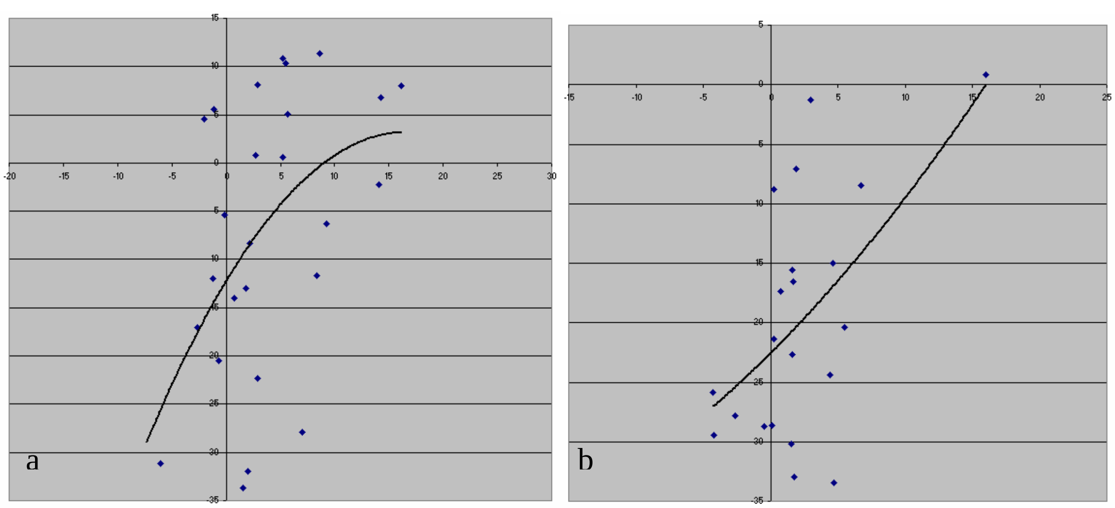

Figure 30

Another area of significant correlation for this time period is found between transects 156 and 176. This is in the vicinity of, but mostly downdrift of, the overwash fan created by

Hurricane Frederic. The correlation coefficient barely meets the critical value: 0.549. Over this 1km length, the gulf shoreline eroded on all but one of the 21 transects with values ranging from +1m to –33m for an average of –20m, while the lagoon shoreline accreted on 17 of the 21 transects with values ranging from –4m to +16m for an average of +2m. Figure 30b shows a positive curvilinear, concave upward relationship.

1989 to 1997

The fifth time period examined is from 1989 to 1997. The average change during this time was +10 meters, about +1.25 meters per year (Figure 31). Beach nourishment projects are

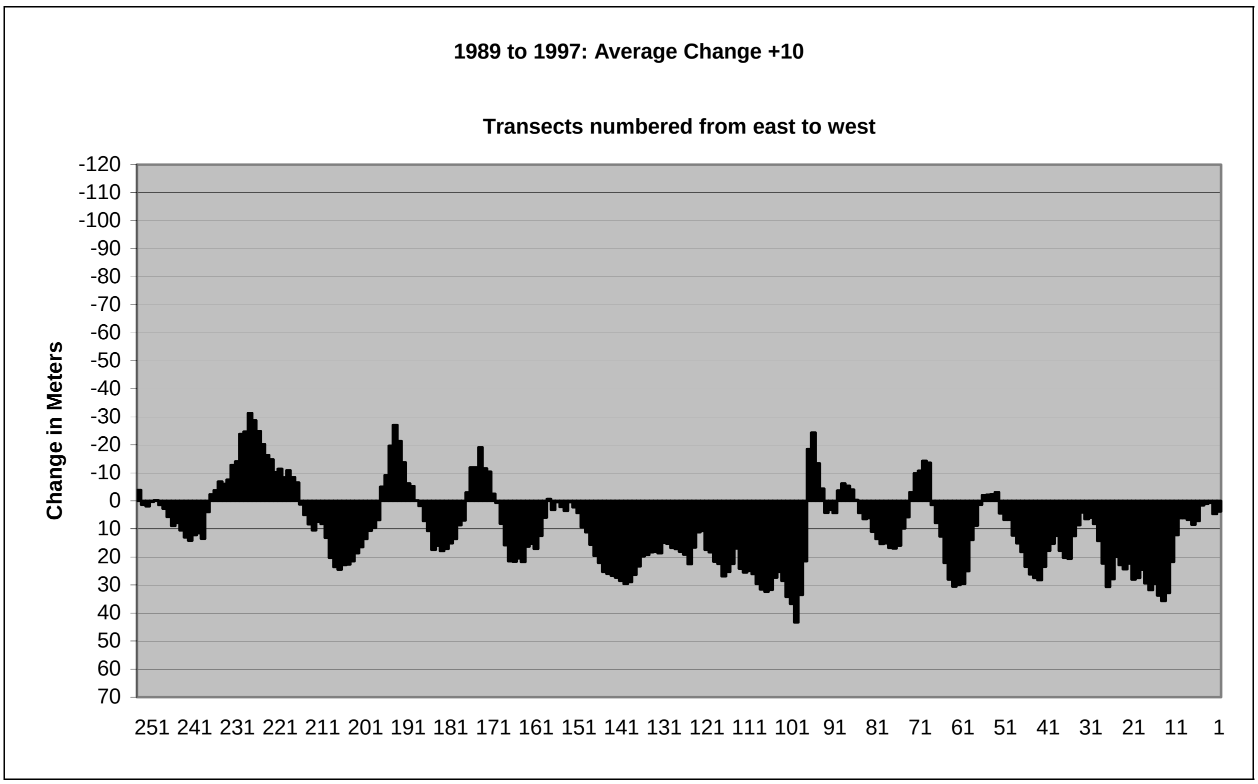

Figure 31 (Gulf shoreline change from 1989 to 1997)

responsible for the accretion. Specific morphologic response depends on the amount of dredging associated with coastal inlets and the location of dredged material placement (Kraus, 2005). In 1992, landowners downdrift of Little Lagoon Pass filed a lawsuit against the Alabama Department of Transportation (ALDOT), formerly the Alabama Highway Department, claiming that they had lost property due to the jetties (Parsons v. Hand *et al*., 1992). ALDOT was ordered to shorten the jetties and to conduct nourishment projects to maintain beach widths downdrift of the western jetty. ALDOT's method is to dredge 150,000m³ of sediment from Little Lagoon, visible in Figure 32 as the dark lines in the center of the lagoon, and deposit it within the first

Figure 32 (1997 aerial photos of Little Lagoon Pass and associated dredging)

1,000' downdrift of the western jetty. Since 1992, nourishment projects have been conducted almost continuously (Appendix B). Wang (2003) noted that some beach fill projects erode much faster than the average erosion rate, creating the need for additional fill. However, the projects

appear to be working – the average change downdrift of the Pass was +9m, or +1.13m per year, with the most significant change occurring immediately west of The Pass and little change thereafter. For the first 2.5km downdrift of the western jetty, the gulf shoreline accreted an average of 24m; after that the shoreline accretes an average of only 2m. Unfortunately, the availability of sediment for future nourishment projects in the long-term is uncertain (Nordstrom, et al, 2004).

Over the eight-year period, Little Lagoon grew from 10,227.9km² to 10,234.5km², a total of 6.6km², or 825m² per year. The area of greatest change occurred between transects 130 and 151 (Figure 33), which is the location of the large overwash fan created by Hurricane Frederic in

Figure 33 (1997 aerial photos overlaid with 1989 lagoon shoreline in white)

1979, discussed earlier. The area eroded 7,614m² during the time period, meaning that Little Lagoon grew by 7.6km² in that one place. When the shape area is divided by half the shape length, the area eroded an average of 6m linearly.

For the time period covering 1989 to 1997, the gulf shoreline accreted +10m and the lagoon's southern shoreline eroded over –1m. The correlation for this period was +0.080, but there were two areas of significant correlation with some overlap (Figure 34). The first exists

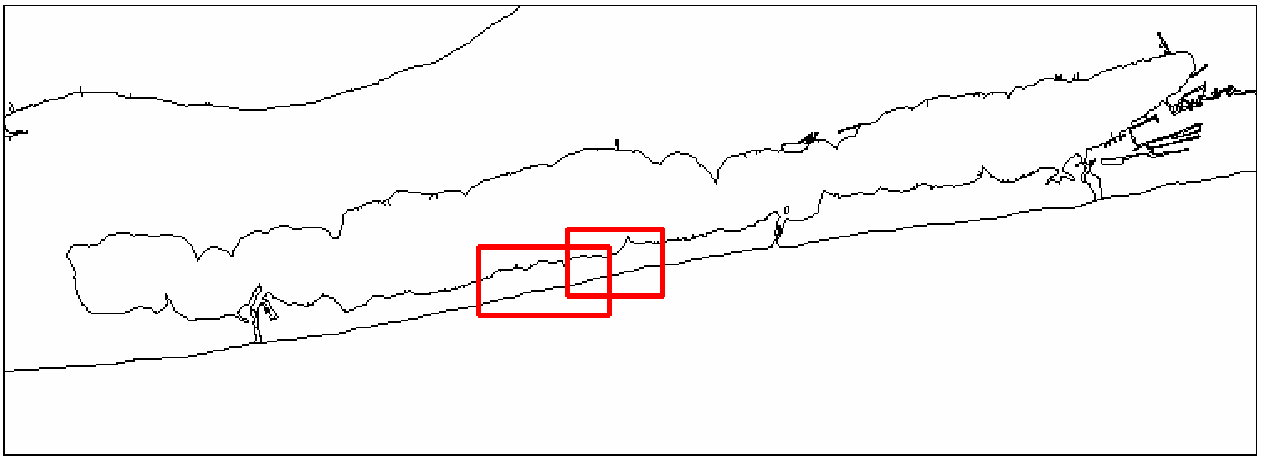

Figure 34 (Area of significant correlation for changes between 1989 and 1997)

between transects 123 and 143, which is coincident with the location of, and mostly updrift of, the overwash fan from 1979. Here, the correlation value was –0.565. Over the 1km, the gulf shoreline accreted on all 21 transects with values ranging from +11m to +30m fro an average of +20m, while the lagoon shoreline eroded on all but three of the 21 transects with values ranging between –10m to +6m for an average of –4m. However, the accretion on the gulf shoreline was part of a larger nourishment project, and probably exaggerates the correlation. Figure 35a shows a negative curvilinear, concave upward relationship.

For the second area, correlation coefficients range from –0.555 to –0.679 between transects 135 and 163, the location of the overwash fan created by Hurricane Frederic. Over the 1.4km, the gulf shoreline accreted on all but one of the 29 transects with values ranging from –1m to +30m for an average of +15m, and the lagoon shoreline eroded on all of the 29 transects

with values ranging from less than –1m to –16m for an average of –6m. The negative correlations reflect the inverse relationship between the gulf and lagoon shorelines. Figure 35b shows a slightly non-monotonic, concave downward relationship.

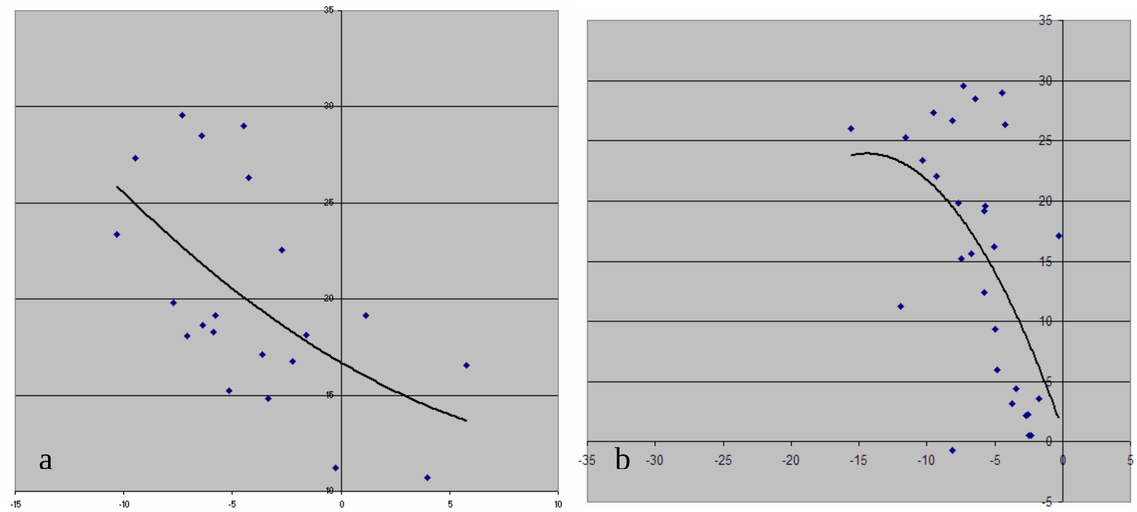

Figure 35

1997 to 2001 (Gulf shoreline)

Between 1997 and 2001, the gulf shoreline accreted an impressive 12m, or +3m per year. Beach nourishment projects are responsible for the accretion. In 2000 and 2001 the city of Gulf Shores conducted numerous nourishment projects, reflected in Figure 36 as the large area of accretion within the first 3.5km of the study area. There, the average change was +43m, almost +11m per year. Downdrift of that, the average change is zero, reinforcing the idea that the nourishment projects related to Little Lagoon Pass continued to be effective.

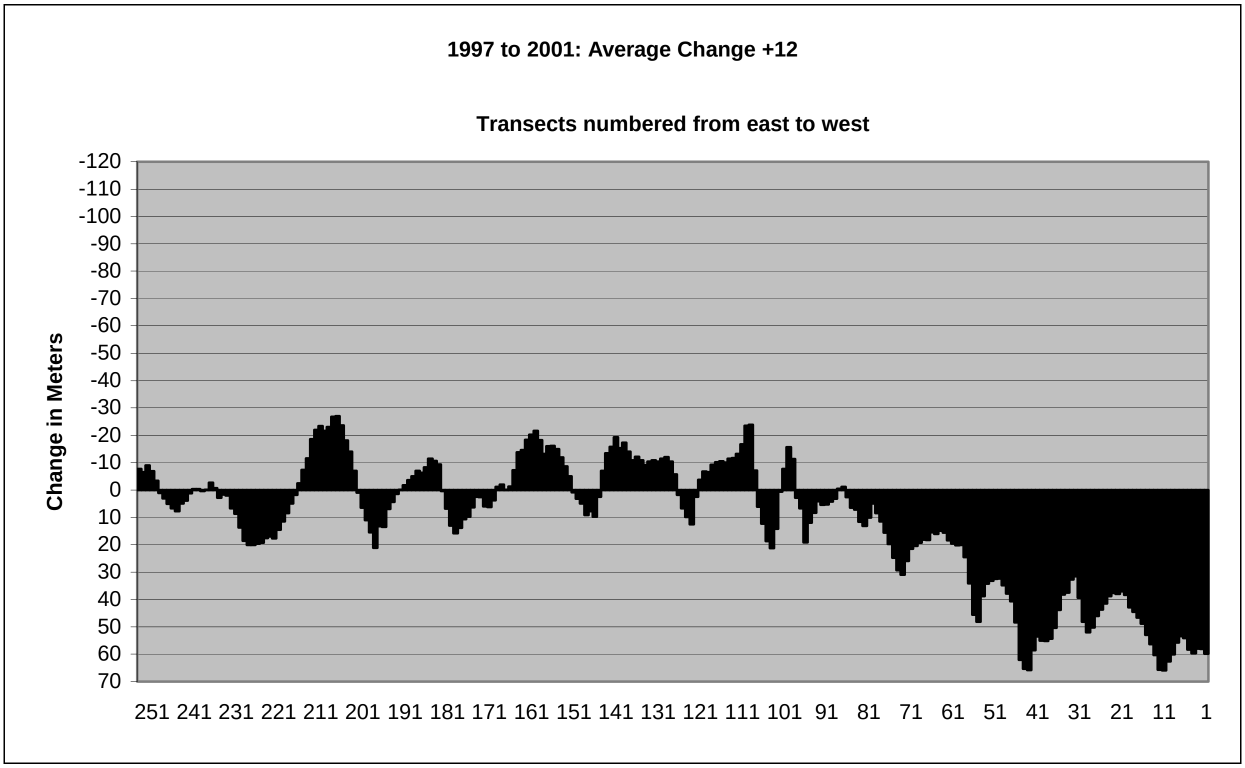

Figure 36 (Gulf shoreline change from 1997 to 2001)

1997 to 2004 (Little Lagoon)

On September 16, 2004, Hurricane Ivan made landfall on Little Lagoon with storm surges ranging between 10' and 15'. Because the aerial photographs of Little Lagoon were taken the day after Hurricane Ivan, they are not useful in actually measuring overall change from 1997 to 2004. However, one change is worth mentioning. Just as Hurricane Frederic deposited an overwash fan of 37km² between transects 135 and 152, Hurricane Ivan deposited over 33km² of sediment on many overwash fans between transect 130 and 182 (Figure 37). The average accretion was over 11m linearly. Some significant changes occurred at The Pass as well (Figure 38), such as crenulate-shaped innerbank erosion as described by Seabergh (2001).

Figure 37 (2004 post-Hurricane Ivan aerial photos overlaid with 1997 lagoon shoreline in blue)

Figure 38 (2004 post-Hurricane Ivan aerial photos of Little Lagoon Pass)

Gradual Changes on Little Lagoon

It should be noted that many changes on Little Lagoon occurred gradually. However, when comparing the 1955 lagoon polygon to the 1997 or 2004 polygon, the greatest changes were still in the location of tidal inlets or overwash fans.

CONCLUSION

Between 1917 and 2001, the gulf shoreline had an average change of –40 meters over the 254 transects. However, some areas of beach eroded almost 120 meters while other portions accreted more than 60 meters. By analyzing the changes in six groups, we are able to see that the greatest changes to occur on the gulf shoreline were related to either the location of natural inlets, human construction, or beach nourishment projects. The single greatest change appears to be the nourishment projects conducted by the City of Gulf Shores in 2000 and 2001.

Little Lagoon has experienced little change between 1955 and 1997. In 1955 the total area of Little Lagoon covered 10,285.9km². By 1997 the total area was reduced to 10,234.5km². That equals a change of –51.4km², meaning that the land is encroaching upon Little Lagoon's estuarine waters at a rate of over 1.2km² per year. The total change is about 0.5%. As seen on the gulf shoreline, the changes very from place to place and from year to year. Of course, it is impossible to account for every change, but the greatest changes occurred at the western and central (later Little Lagoon Pass) tidal inlets, the hurricane overwash fans deposited in 1979 and 2004, and one area of significant erosion that I assume to be the result of human impacts between 1960 and 1970.

Weak correlations between the gulf shoreline and the lagoon's southern shoreline exist for each time period when all 254 transects are used. But much stronger correlations are seen when measured over 1km sections, some reaching +0.917. The most statistically significant correlations exist at the same places that we find the greatest changes to both the gulf and lagoon shorelines: near tidal inlets and hurricane overwash fans.

Little Lagoon and the gulf shoreline adjacent to it represent a unique area to study changes associated with natural inlets, major storms, coastal engineering, and nourishment

projects. The area continues to develop despite the devastation caused by double-digit storm surges from major hurricanes in 2004 and 2005. An understanding of beach behavior in response to future engineering can be gained by observing coastal morphology of the proposed engineering site. By analyzing shoreline change in larger-scales and shorter-terms, this study hopefully provided the type of qualitative analysis called for by Cooper and Pilkey (2004b).

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Appendix A

Maps and Charts

1. **Historic Maps** (downloaded from University of Alabama's Historic Map Archive at http://alabamamaps.ua.edu/historicalmaps/index.html).

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3. Topological Charts

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Appendix B

Little Lagoon Pass Dredging Projects

Project Number	Begin Date	End Date
Beach Restoration	04/18/1992	06/25/1992
99-709-022-182-340	01/25/1993	02/07/1993
	02/23/1993	03/03/1993
	03/24/1993	03/31/1993
	04/29/1993	05/05/1993
	06/03/1993	06/07/1993
	07/08/1993	07/14/1993
99-709-022-182-344	09/10/1993	09/18/1993
	10/14/1993	10/24/1993
99-509-022-182-348	12/03/1993	01/06/1994
	02/04/1994	03/06/1994
	06/21/1994	06/27/1994
	09/22/1994	09/30/1994
	10/17/1994	10/21/1994
	12/16/1994	12/22/1994
	01/25/1995	02/20/1995
	04/03/1995	04/14/1995
	06/15/1995	06/23/1995
	08/07/1995	08/19/1995
	09/08/1995	09/16/1995
	11/05/1995	11/10/1995
	04/05/1996	04/26/1996
99-509-022-182-648	06/17/1996	06/25/1996
	08/11/1996	08/21/1996
	10/09/1996	10/18/1996
	12/03/1996	01/23/1997
	02/25/1997	03/06/1997
	04/19/1997	05/02/1997
	06/23/1997	07/04/1997
	09/08/1997	09/12/1997
	10/27/1997	12/19/1997
	03/03/1998	04/24/1998
	06/29/1998	07/25/1998
	08/31/1998	11/17/1998

Project Number	Begin Date	End Date
99-509-022-182-848	11/18/1998	12/16/1998
	03/22/1999	04/28/1999
	06/19/1999	07/19/1999
	10/22/1999	12/20/1999
	02/16/2000	03/11/2000
	05/02/2000	05/11/2000
	07/06/2000	07/19/2000
	09/06/2000	12/13/2000
	04/11/2001	05/13/2001
99-509-022-182-148	07/13/2001	08/21/2001
	09/27/2001	11/02/2001
	12/03/2001	01/31/2002
	04/18/2002	05/15/2002
	09/16/2002	11/20/2002
99-509-022-182-348	11/17/2003	11/27/2003
	12/20/2003	12/23/2003
	08/31/2004	09/13/2004